

## Appendix A7. Public Meeting Handouts

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Issue: *Ecological Economics Reviews***Full cost accounting for the life cycle of coal**

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Each stage in the life cycle of coal—extraction, transport, processing, and combustion—generates a waste stream and carries multiple hazards for health and the environment. These costs are external to the coal industry and are thus often considered “externalities.” We estimate that the life cycle effects of coal and the waste stream generated are costing the U.S. public a third to over one-half of a trillion dollars annually. Many of these so-called externalities are, moreover, cumulative. Accounting for the damages conservatively doubles to triples the price of electricity from coal per kWh generated, making wind, solar, and other forms of nonfossil fuel power generation, along with investments in efficiency and electricity conservation methods, economically competitive. We focus on Appalachia, though coal is mined in other regions of the United States and is burned throughout the world.

**Keywords:** coal; environmental impacts; human and wildlife health consequences; carbon capture and storage; climate change

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**Introduction**

Coal is currently the predominant fuel for electricity generation worldwide. In 2005, coal use generated 7,334 TWh (1 terawatt hour = 1 trillion watt-hours, a measure of power) of electricity, which was then 40% of all electricity worldwide. In 2005, coal-derived electricity was responsible for 7.856 Gt of CO<sub>2</sub> emissions or 30% of all worldwide carbon dioxide (CO<sub>2</sub>) emissions, and 72% of CO<sub>2</sub> emissions from power generation (one gigaton = one billion tons; one metric ton = 2,204 pounds.)<sup>1</sup> Non-power-generation uses of coal, including industry (e.g., steel, glass-blowing), transport, residential services, and agriculture, were responsible for another 3.124 Gt of CO<sub>2</sub>, bringing coal’s total burden of CO<sub>2</sub> emissions to 41% of worldwide CO<sub>2</sub> emissions in 2005.<sup>1</sup>

By 2030, electricity demand worldwide is projected to double (from a 2005 baseline) to 35,384 TWh, an annual increase of 2.7%, with the quantity of electricity generated from coal growing 3.1% per annum to 15,796 TWh.<sup>1</sup> In this same time period, worldwide CO<sub>2</sub> emissions are projected to grow 1.8% per year, to 41.905 Gt, with emissions from the coal-power electricity sector projected to grow 2.3% per year to 13.884 Gt.<sup>1</sup>

In the United States, coal has produced approximately half of the nation’s electricity since 1995,<sup>2</sup> and demand for electricity in the United States is projected to grow 1.3% per year from 2005 to 2030, to 5,947 TWh.<sup>1</sup> In this same time period, coal-derived electricity is projected to grow 1.5% per year to 3,148 TWh (assuming no policy changes from the present).<sup>1</sup> Other agencies show similar projections; the U.S. Energy Information Administration (EIA)

projects that U.S. demand for coal power will grow from 1,934 TWh in 2006 to 2,334 TWh in 2030, or 0.8% growth per year.<sup>3</sup>

To address the impact of coal on the global climate, carbon capture and storage (CCS) has been proposed. The costs of plant construction and the “energy penalty” from CCS, whereby 25–40% more coal would be needed to produce the same amount of energy, would increase the amount of coal mined, transported, processed, and combusted, as well as the waste generated, to produce the same amount of electricity.<sup>1,4</sup> Construction costs, compression, liquefaction and injection technology, new infrastructure, and the energy penalty would nearly double the costs of electricity generation from coal plants using current combustion technology (see Table 2).<sup>5</sup>

Adequate energy planning requires an accurate assessment of coal reserves. The total recoverable reserves of coal worldwide have been estimated to be approximately 929 billion short tons (one short ton = 2,000 pounds).<sup>2</sup> Two-thirds of this is found in four countries: U.S. 28%; Russia 19%; China 14%, and India 7%.<sup>6</sup> In the United States, coal is mined in 25 states.<sup>2</sup> Much of the new mining in Appalachia is projected to come from mountaintop removal (MTR).<sup>2</sup>

### Box 1.

#### Peak Coal?

With 268 billion tons of estimated recoverable reserves (ERR) reported by the U.S. Energy Information Administration (EIA), it is often estimated that the United States has “200 years of coal” supply.<sup>7</sup> However, the EIA has acknowledged that what the EIA terms ERR cannot technically be called “reserves” because they have not been analyzed for profitability of extraction.<sup>7</sup> As a result, the oft-repeated claim of a “200 year supply” of U.S. coal does not appear to be grounded on thorough analysis of economically recoverable coal supplies.

Reviews of existing coal mine lifespan and economic recoverability reveal serious constraints on existing coal production and numerous constraints facing future coal mine expansion. Depending on the resolution of the geologic, economic, legal, and transportation constraints facing future coal mine expansion, the planning horizon for moving beyond coal may be as short as 20–30 years.<sup>8–11</sup>

Recent multi-Hubbert cycle analysis estimates global peak coal production for 2011 and U.S. peak coal production for 2015.<sup>12</sup> The potential of “peak coal” thus raises questions for investments in coal-fired plants and CCS.

Worldwide, China is the chief consumer of coal, burning more than the United States, the European Union, and Japan combined. With worldwide demand for electricity, and oil and natural gas insecurities growing, the price of coal on global markets doubled from March 2007 to March 2008: from \$41 to \$85 per ton.<sup>13</sup> In 2010, it remained in the \$70+/ton range.

Coal burning produces one and a half times the CO<sub>2</sub> emissions of oil combustion and twice that from burning natural gas (for an equal amount of energy produced). The process of converting coal-to-liquid (not addressed in this study) and burning that liquid fuel produces especially high levels of CO<sub>2</sub> emissions.<sup>13</sup> The waste of energy due to inefficiencies is also enormous. Energy specialist Amory Lovins estimates that after mining, processing, transporting and burning coal, and transmitting the electricity, only about 3% of the energy in the coal is used in incandescent light bulbs.<sup>14</sup>

Thus, in the United States in 2005, coal produced 50% of the nation’s electricity but 81% of the CO<sub>2</sub> emissions.<sup>1</sup> For 2030, coal is projected to produce 53% of U.S. power and 85% of the U.S. CO<sub>2</sub> emissions from electricity generation. None of these figures includes the additional life cycle greenhouse gas (GHG) emissions from coal, including methane from coal mines, emissions from coal transport, other GHG emissions (e.g., particulates or black carbon), and carbon and nitrous oxide (N<sub>2</sub>O) emissions from land transformation in the case of MTR coal mining.

Coal mining and combustion releases many more chemicals than those responsible for climate forcing. Coal also contains mercury, lead, cadmium, arsenic, manganese, beryllium, chromium, and other toxic, and carcinogenic substances. Coal crushing, processing, and washing releases tons of particulate matter and chemicals on an annual basis and contaminates water, harming community public health and ecological systems.<sup>15–19</sup> Coal combustion also results in emissions of NO<sub>x</sub>, sulfur dioxide (SO<sub>2</sub>),

the particulates PM<sub>10</sub> and PM<sub>2.5</sub>, and mercury; all of which negatively affect air quality and public health.<sup>20–23</sup>

In addition, 70% of rail traffic in the United States is dedicated to shipping coal, and rail transport is associated with accidents and deaths.<sup>20</sup> If coal use were to be expanded, land and transport infrastructure would be further stressed.

## Summary of methods

Life cycle analysis, examining all stages in using a resource, is central to the full cost accounting needed to guide public policy and private investment. A previous study examined the life cycle stages of oil, but without systematic quantification.<sup>24</sup> This paper is intended to advance understanding of the measurable, quantifiable, and qualitative costs of coal.

In order to rigorously examine these different damage endpoints, we examined the many stages in the life cycle of coal, using a framework of environmental externalities, or “hidden costs.” Externalities occur when the activity of one agent affects the well-being of another agent outside of any type of market mechanism—these are often not taken into account in decision making and when they are not accounted for, they can distort the decision-making process and reduce the welfare of society.<sup>20</sup> This work strives to derive monetary values for these externalities so that they can be used to inform policy making.

This paper tabulates a wide range of costs associated with the full life cycle of coal, separating those that are quantifiable and monetizable; those that are quantifiable, but difficult to monetize; and those that are qualitative.

A literature review was conducted to consolidate all impacts of coal-generated electricity over its life cycle, monetize and tabulate those that are monetizable, quantify those that are quantifiable, and describe the qualitative impacts. Since there is some uncertainty in the monetization of the damages, low, best, and high estimates are presented. The monetizable impacts found are damages due to climate change; public health damages from NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>2.5</sub>, and mercury emissions; fatalities of members of the public due to rail accidents during coal transport; the public health burden in Appalachia associated with coal mining; government subsidies; and lost value of abandoned mine lands. All values

are presented in 2008 US\$. Much of the research we draw upon represented uncertainty by presenting low and/or high estimates in addition to best estimates. Low and high values can indicate both uncertainty in parameters and different assumptions about the parameters that others used to calculate their estimates. Best estimates are not weighted averages, and are derived differently for each category, as explained below.

Climate impacts were monetized using estimates of the social cost of carbon—the valuation of the damages due to emissions of one metric ton of carbon, of \$30/ton of CO<sub>2</sub>equivalent (CO<sub>2</sub>e),<sup>20</sup> with low and high estimates of \$10/ton and \$100/ton. There is uncertainty around the total cost of climate change and its present value, thus uncertainty concerning the social cost of carbon derived from the total costs. To test for sensitivity to the assumptions about the total costs, low and high estimates of the social cost of carbon were used to produce low and high estimates for climate damage, as was done in the 2009 National Research Council (NRC) report on the “Hidden Costs of Energy.”<sup>20</sup> To be consistent with the NRC report, this work uses a low value of \$10/ton CO<sub>2</sub>e and a high value of \$100/ton CO<sub>2</sub>e.

All public health impacts due to mortality were valued using the value of statistical life (VSL). The value most commonly used by the U.S. Environmental Protection Agency (EPA), and used in this paper, is the central estimate of \$6 million 2000 US\$, or \$7.5 million in 2008 US\$.<sup>20</sup>

Two values for mortality risk from exposure to air pollutants were found and differed due to different concentration-response functions—increases in mortality risk associated with exposure to air pollutants. The values derived using the lower of the two concentration-response functions is our low estimate, and the higher of the two concentration-response functions is our best and high estimate, for reasons explained below. The impacts on cognitive development and cardiovascular disease due to mercury exposure provided low, best, and high estimates, and these are presented here.

Regarding federal subsidies, two different estimates were found. To provide a conservative best estimate, the lower of the two values represents our low and best estimate, and the higher represents our high estimate. For the remaining costs, one point estimate was found in each instance, representing our low, best, and high estimates.

The monetizable impacts were normalized to per kWh of electricity produced, based on EIA estimates of electricity produced from coal, as was done in the NRC report tabulating externalities due to coal.<sup>2,20</sup> Some values were for all coal mining, not just for the portion emitted due to coal-derived electricity. To correct for this, the derived values were multiplied by the proportion of coal that was used for electrical power, which was approximately 90% in all years analyzed. The additional impacts from nonpower uses of coal, however, are not included in this analysis but do add to the assessment of the complete costs of coal.

To validate the findings, a life cycle assessment of coal-derived electricity was also performed using the Ecoinvent database in SimaPro v 7.1.<sup>25</sup> Health-related impact pathways were monetized using the value of disability-adjusted life-years from ExternE,<sup>26</sup> and the social costs of carbon.<sup>20</sup> Due to data limitations, this method could only be used to validate damages due to a subset of endpoints.

## Box 2.

### Summary Stats

1. Coal accounted for 25% of global energy consumption in 2005, but generated 41% of the CO<sub>2</sub> emissions that year.
2. In the United States, coal produces just over 50% of the electricity, but generates over 80% of the CO<sub>2</sub> emissions from the utility sector.<sup>2</sup>
3. Coal burning produces one and a half times more CO<sub>2</sub> emissions than does burning oil and twice that from burning natural gas (to produce an equal amount of energy).
4. The energy penalty from CCS (25–40%) would increase the amount of coal mined, transported, processed, and combusted, and the waste generated.<sup>4</sup>
5. Today, 70% of rail traffic in the United States is dedicated to shipping coal.<sup>20</sup> Land and transport would be further stressed with greater dependence on coal.

## Life cycle impacts of coal

The health and environmental hazards associated with coal stem from extraction, processing, transportation and combustion of coal; the aerosolized,

solid, and liquid waste stream associated with mining, processing, and combustion; and the health, environmental, and economic impacts of climate change (Table 1).

### *Underground mining and occupational health*

The U.S. Mine Safety and Health Administration (MSHA) and the National Institute for Occupational Safety and Health (NIOSH) track occupational injuries and disabilities, chronic illnesses, and mortality in miners in the United States. From 1973 to 2006 the incidence rate of all nonfatal injuries decreased from 1973 to 1987, then increased dramatically in 1988, then decreased from 1988 to 2006.<sup>27</sup> Major accidents still occur. In January 2006, 17 miners died in Appalachian coal mines, including 12 at the Sago mine in West Virginia, and 29 miners died at the Upper Big Branch Mine in West VA on April 5, 2010. Since 1900 over 100,000 have been killed in coal mining accidents in the United States.<sup>14</sup>

In China, underground mining accidents cause 3,800–6,000 deaths annually,<sup>28</sup> though the number of mining-related deaths has decreased by half over the past decade. In 2009, 2,631 coal miners were killed by gas leaks, explosions, or flooded tunnels, according to the Chinese State Administration of Work Safety.<sup>29</sup>

Black lung disease (or pneumoconiosis), leading to chronic obstructive pulmonary disease, is the primary illness in underground coal miners. In the 1990s, over 10,000 former U.S. miners died from coal workers' pneumoconiosis and the prevalence has more than doubled since 1995.<sup>30</sup> Since 1900 coal workers' pneumoconiosis has killed over 200,000 in the United States.<sup>14</sup> These deaths and illnesses are reflected in wages and workers' comp, costs considered internal to the coal industry, but long-term support often depends on state and federal funds.

Again, the use of "coking" coal used in industry is also omitted from this analysis: a study performed in Pittsburgh demonstrated that rates of lung cancer for those working on a coke oven went up two and one-half times, and those working on the top level had the highest (10-fold) risk.<sup>31</sup>

### *Mountaintop removal*

MTR is widespread in eastern Kentucky, West Virginia, and southwestern Virginia. To expose coal seams, mining companies remove forests and fragment rock with explosives. The rubble or "spoil"

then sits precariously along edges and is dumped in the valleys below. MTR has been completed on approximately 500 sites in Kentucky, Virginia, West Virginia, and Tennessee,<sup>32</sup> completely altering some 1.4 million acres, burying 2,000 miles of streams.<sup>33</sup> In Kentucky, alone, there are 293 MTR sites, over 1,400 miles of streams damaged or destroyed, and 2,500 miles of streams polluted.<sup>34–36</sup> Valley fill and other surface mining practices associated with MTR bury headwater streams and contaminate surface and groundwater with carcinogens and heavy metals<sup>16</sup> and are associated with reports of cancer clusters,<sup>37</sup> a finding that requires further study.

The deforestation and landscape changes associated with MTR have impacts on carbon storage and water cycles. Life cycle GHG emissions from coal increase by up to 17% when those from deforestation and land transformation by MTR are included.<sup>38</sup> Fox and Campbell estimated the resulting emissions of GHGs due to land use changes in the Southern Appalachian Forest, which encompasses areas of southern West Virginia, eastern Kentucky, southwestern Virginia, and portions of eastern Tennessee, from a baseline of existing forestland.<sup>38</sup> They estimated that each year, between 6 and 6.9 million tons of CO<sub>2</sub>e are emitted due to removal of forest plants and decomposition of forest litter, and possibly significantly more from the mining “spoil” and lost soil carbon.

The fate of soil carbon and the fate of mining spoil, which contains high levels of coal fragments, termed “geogenic organic carbon,” are extremely uncertain and the results depend on mining practices at particular sites; but they may represent significant emissions. The Fox and Campbell<sup>38</sup> analysis determined that the worst-case scenario is that all soil carbon is lost and that all carbon in mining spoil is emitted—representing emissions of up to 2.6 million tons CO<sub>2</sub>e from soil and 27.5 million tons CO<sub>2</sub>e from mining spoil. In this analysis, the 6 million tons CO<sub>2</sub>e from forest plants and forest litter represents our low and best estimates for all coal use, and 37 million tons CO<sub>2</sub>e (the sum of the high bound of forest plants and litter, geogenic organic carbon, and the forest soil emissions) represents our high, upper bound estimate of emissions for all coal use. In the years Fox and Campbell studied, 90.5% of coal was used for electricity, so we attribute 90.5% of these emissions to coal-derived power.<sup>2</sup> To mon-

etize and bound our estimate for damages due to emissions from land disturbance, our point estimate for the cost was calculated using a social cost of carbon of \$30/ton CO<sub>2</sub>e and our point estimate for emissions; the high-end estimate was calculated using the high-end estimate of emissions and a social cost of carbon of \$100/ton CO<sub>2</sub>e; and the low estimate was calculated using the point estimate for emissions and the \$10/ton low estimate for the social cost of carbon.<sup>20</sup> Our best estimate is therefore \$162.9 million, with a range from \$54.3 million and \$3.35 billion, or 0.008¢/kWh, ranging from 0.003 ¢/kWh to 0.166 ¢/kWh.

The physical vulnerabilities for communities near MTR sites include mudslides and dislodged boulders and trees, and flash floods, especially following heavy rain events. With climate change, heavy rainfall events (2, 4, and 6 inches/day) have increased in the continental United States since 1970, 14%, 20%, and 27% respectively.<sup>39,40</sup>

Blasting to clear mountain ridges adds an additional assault to surrounding communities.<sup>16</sup> The blasts can damage houses, other buildings, and infrastructure, and there are numerous anecdotal reports that the explosions and vibrations are taking a toll on the mental health of those living nearby.

Additional impacts include losses in property values, timber resources, crops (due to water contamination), plus harm to tourism, corrosion of buildings and monuments, dust from mines and explosions, ammonia releases (with formation of ammonium nitrate), and releases of methane.<sup>41</sup>

### *Methane*

In addition to being a heat-trapping gas of high potency, methane adds to the risk of explosions, and fires at mines.<sup>20,42</sup> As of 2005, global atmospheric methane levels were approximately 1,790 parts per billion (ppb), which is an 27 ppb increase over 1998.<sup>43</sup> Methane is emitted during coal mining and it is 25 times more potent than CO<sub>2</sub> during a 100-year timeframe (this is the 100-year global warming potential, a common metric in climate science and policy used to normalize different GHGs to carbon equivalence). When methane decays, it can yield CO<sub>2</sub>, an effect that is not fully assessed in this equivalency value.<sup>43</sup>

According to the EIA,<sup>2</sup> 71,100,000 tons CO<sub>2</sub>e of methane from coal were emitted in 2007 but

**Table 1. The life cycle impact of the U.S. coal industry**

	Economic	Human health	Environment	Other
Underground coal mining	1. Federal and state subsidies of coal industry	1. Increased mortality and morbidity in coal communities due to mining pollution 2. Threats remaining from abandoned mine lands	1. Methane emissions from coal leading to climate change 2. Remaining damage from abandoned mine lands	
MTR mining	1. Tourism loss 2. Significantly lower property values 3. Cost to taxpayers of environmental mitigation and monitoring (both mining and disposal stages) 4. Population declines	1. Contaminated streams 2. Direct trauma in surrounding communities 3. Additional mortality and morbidity in coal communities due to increased levels of air particulates associated with MTR mining (vs. underground mining) 4. Higher stress levels	1. Loss of biodiversity 2. Sludge and slurry ponds 3. Greater levels of air particulates 4. Loss and contamination of streams	
Coal mining	1. Opportunity costs of bypassing other types of economic development (especially for MTR mining) 2. Federal and state subsidies of coal industry 3. Economic boom and bust cycle in coal mining communities 4. Cost of coal industry litigation	1. Workplace fatalities and injuries of coal miners 2. Morbidity and mortality of mine workers resulting from air pollution (e.g., black lung, silicosis) 3. Increased mortality and morbidity in coal communities due to mining pollution 4. Increased morbidity and mortality due to increased air particulates in communities proximate to MTR mining	1. Destruction of local habitat and biodiversity to develop mine site 2. Methane emissions from coal leading to climate change 3. Loss of habitat and streams from valley fill (MTR) 4. Acid mine drainage	1. Infrastructure damage due to mudslides following MTR 2. Damage to surrounding infrastructure from subsidence 3. Damages to buildings and other infrastructure due to mine blasting 4. Loss of recreation availability in coal mining communities

*Continued*

**Table 1. Continued**

	Economic	Human health	Environment	Other
	5. Damage to farmland and crops resulting from coal mining pollution	5. Hospitalization costs resulting from increased morbidity in coal communities	5. Incomplete reclamation following mine use	5. Population losses in abandoned coal-mining communities
	6. Loss of income from small scale forest gathering and farming (e.g., wild ginseng, mushrooms) due to habitat loss	6. Local health impacts of heavy metals in coal slurry	6. Water pollution from runoff and waste spills	
	7. Loss of tourism income	7. Health impacts resulting from coal slurry spills and water contamination	7. Remaining damage from abandoned mine lands	
	8. Lost land required for waste disposal	8. Threats remaining from abandoned mine lands; direct trauma from loose boulders and felled trees	8. Air pollution due to increased particulates from MTR mining	
	9. Lower property values for homeowners	9. Mental health impacts		
	10. Decrease in mining jobs in MTR mining areas	10. Dental health impacts reported, possibly from heavy metals		
		11. Fungal growth after flooding		
Coal transportation	1. Wear and tear on aging railroads and tracks	1. Death and injuries from accidents during transport	1. GHG emissions from transport vehicles	1. Damage to rail system from coal transportation
		2. Impacts from emissions during transport	2. Damage to vegetation resulting from air pollution	2. Damage to roadways due to coal trucks
Coal combustion	1. Federal and state subsidies for the coal industry	1. Increased mortality and morbidity due to combustion pollution	1. Climate change due to CO <sub>2</sub> and NO <sub>x</sub> derived N <sub>2</sub> O emissions	1. Corrosion of buildings and monuments from acid rain
	2. Damage to farmland and crops resulting from coal combustion pollution	2. Hospitalization costs resulting from increased morbidity in coal communities	2. Environmental contamination as a result of heavy metal pollution (mercury, selenium, arsenic)	2. Visibility impairment from NO <sub>x</sub> emissions

*Continued*



**Table 1. Continued**

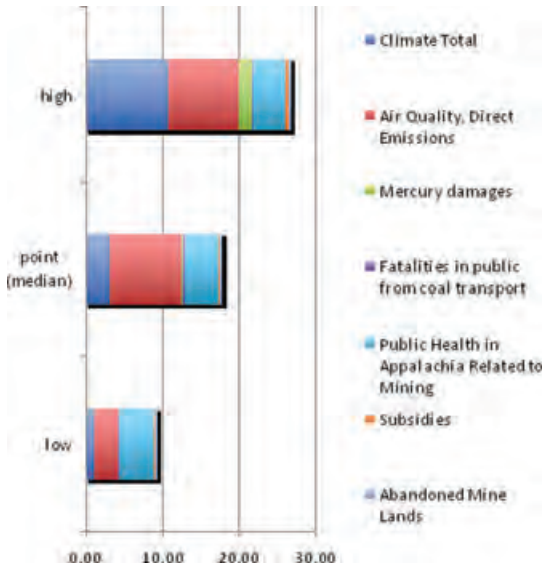
	Economic	Human health	Environment	Other
		3. Higher frequency of sudden infant death syndrome in areas with high quantities of particulate pollution	3. Impacts of acid rain derived from nitrogen oxides and SO <sub>2</sub>	
		4. See Levy <i>et al.</i> <sup>21</sup>	4. Environmental impacts of ozone and particulate emissions	
			5. Soil contamination from acid rain	
			6. Destruction of marine life from mercury pollution and acid rain	
			7. Freshwater use in coal powered plants	
Waste disposal		1. Health impacts of heavy metals and other contaminants in coal ash and other waste	1. Impacts on surrounding ecosystems from coal ash and other waste	
		2. Health impacts, trauma and loss of property following coal ash spills	2. Water pollution from runoff and fly ash spills	
Electricity transmission	1. Loss of energy in the combustion and transmission phases		1. Disturbance of ecosystems by utility towers and rights of way	1. Vulnerability of electrical grid to climate change associated disasters

only 92.7% of this coal is going toward electricity. This results in estimated damages of \$2.05 billion, or 0.08¢/kWh, with low and high estimates of \$684 million and \$6.84 billion, or 0.034¢/kWh, and 0.34¢/kWh, using the low and high estimates for the social cost of carbon.<sup>20</sup> Life cycle assessment results, based on 2004 data and emissions from a subset of power plants, indicated 0.037 kg of CO<sub>2</sub>e of methane emitted per kWh of electricity produced. With the best estimate for the social cost of carbon, this leads to an estimated cost of \$2.2 billion, or 0.11¢/kWh. The differences are due to differences in data, and

data from a different years. (See Fig. 1 for summary of external costs per kWh.)

**Impoundments**

Impoundments are found all along the periphery and at multiple elevations in the areas of MTR sites; adjacent to coal processing plants; and as coal combustion waste (“fly ash”) ponds adjacent to coal-fired power plants.<sup>47</sup> Their volume and composition have not been calculated.<sup>48</sup> For Kentucky, the number of known waste and slurry ponds alongside MTR sites and processing plants is 115.<sup>49</sup> These

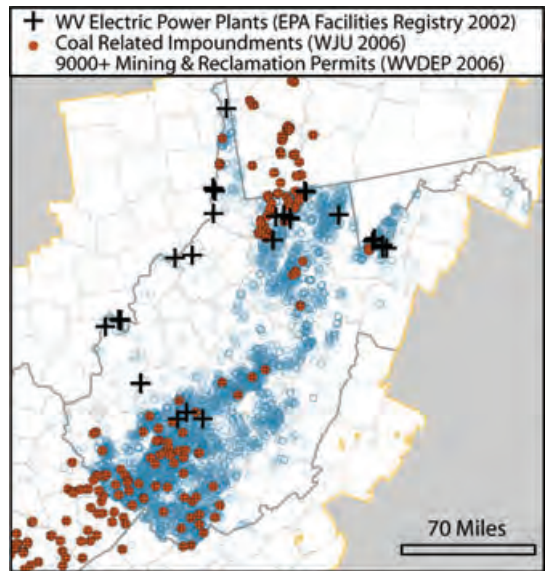


**Figure 1.** This graph shows the best estimates of the externalities due to coal, along with low and high estimates, normalized to ¢ per kWh of electricity produced. (In color in *Annals* online.)

sludge, slurry and coal combustion waste (CCW) impoundments are considered by the EPA to be significant contributors to water contamination in the United States. This is especially true for impoundments situated atop previously mined and potentially unstable sites. Land above tunnels dug for long-haul and underground mining are at risk of caving. In the face of heavier precipitation events, unlined containment dams, or those lined with dried slurry are vulnerable to breaching and collapse (Fig. 2).

**Processing plants**

After coal is mined, it is washed in a mixture of chemicals to reduce impurities that include clay, non-carbonaceous rock, and heavy metals to prepare for use in combustion.<sup>50</sup> Coal slurry is the by-product of these coal refining plants. In West Virginia, there are currently over 110 billion gallons of coal slurry permitted for 126 impoundments.<sup>49,51</sup> Between 1972 and 2008, there were 53 publicized coal slurry spills in the Appalachian region, one of the largest of which was a 309 million gallon spill that occurred in Martin County, KY in 2000.<sup>48</sup> Of the known chemicals used and generated in processing coal, 19 are known cancer-causing agents, 24 are linked to lung and heart damage, and several remain untested as to their health effects.<sup>52,53</sup>



**Figure 2.** Electric power plants, impoundments (sludge and slurry ponds, CCW, or “fly ash”), and sites slated for reclamation in West Virginia.<sup>44–46</sup> (In color in *Annals* online.) Source: Hope Childers, Wheeling Jesuit University.

**Coal combustion waste or fly ash**

CCW or fly ash—composed of products of combustion and other solid waste—contains toxic chemicals and heavy metals; pollutants known to cause cancer, birth defects, reproductive disorders, neurological damage, learning disabilities, kidney disease, and diabetes.<sup>47,54</sup> A vast majority of the over 1,300 CCW impoundment ponds in the United States are poorly constructed, increasing the risk that waste may leach into groundwater supplies or nearby bodies of water.<sup>55</sup> Under the conditions present in fly ash ponds, contaminants, particularly arsenic, antimony, and selenium (all of which can have serious human health impacts), may readily leach or migrate into the water supplied for household and agricultural use.<sup>56</sup>

According to the EPA, annual production of CCW increased 30% per year between 2000 and 2004, to 130 million tons, and is projected to increase to over 170 million tons by 2015.<sup>57</sup> Based on a series of state estimates, approximately 20% of the total is injected into abandoned coal mines.<sup>58</sup>

In Kentucky, alone, there are 44 fly ash ponds adjacent to the 22 coal-fired plants. Seven of these ash ponds have been characterized as “high hazard”

by the EPA, meaning that if one of these impoundments spilled, it would likely cause significant property damage, injuries, illness, and deaths. Up to 1 in 50 residents in Kentucky, including 1 in 100 children, living near one of the fly ash ponds are at risk of developing cancer as a result of water- and air-borne exposure to waste.<sup>47</sup>

### Box 3.

#### Tennessee Valley Authority Fly Ash Pond Spill

On December 2, 2008 an 84-acre CCW containment area spilled when the dike ruptured at the Tennessee Valley Authority Kingston Fossil Plant CCW impoundment, following heavy rains. Over one billion gallons of fly ash slurry spilled across 300 acres.

### Local water contamination

Over the life cycle of coal, chemicals are emitted directly and indirectly into water supplies from mining, processing, and power plant operations. Chemicals in the waste stream include ammonia, sulfur, sulfate, nitrates, nitric acid, tars, oils, fluorides, chlorides, and other acids and metals, including sodium, iron, cyanide, plus additional unlisted chemicals.<sup>16,50</sup>

Spath and colleagues<sup>50</sup> found that these emissions are small in comparison to the air emissions. However, a more recent study performed by Koornneef and colleagues<sup>59</sup> using up-to-date data on emissions and impacts, found that emissions and seepage of toxins and heavy metals into fresh and marine water were significant. Elevated levels of arsenic in drinking water have been found in coal mining areas, along with ground water contamination consistent with coal mining activity in areas near coal mining facilities.<sup>16,17,60,61</sup> In one study of drinking water in four counties in West Virginia, heavy metal concentrations (thallium, selenium, cadmium, beryllium, barium, antimony, lead, and arsenic) exceeded drinking water standards in one-fourth of the households.<sup>48</sup> This mounting evidence indicates that more complete coverage of water sampling is needed throughout coal-field regions.

### Carcinogen emissions

Data on emissions of carcinogens due to coal mining and combustion are available in the Ecoin-

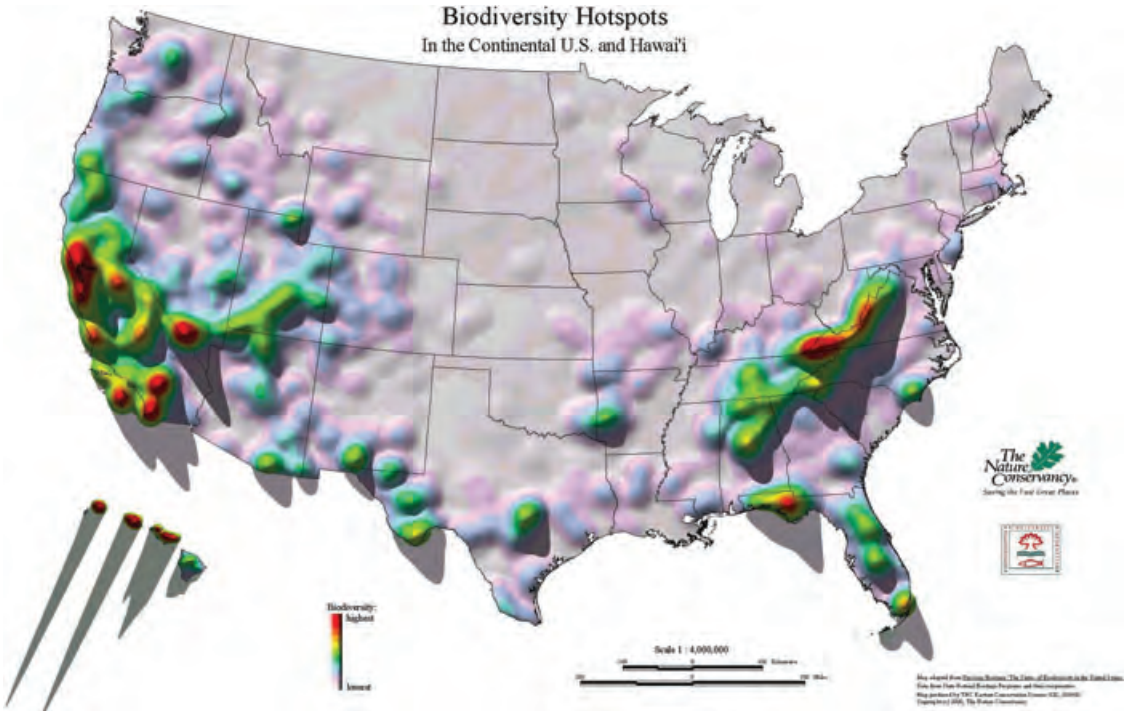
vent database.<sup>25</sup> The eco-indicator impact assessment method was used to estimate health damages in disability-adjusted life years due to these emissions,<sup>25</sup> and were valued using the VSL-year.<sup>26</sup> This amounted to \$11 billion per year, or 0.6 ¢/kWh, though these may be significant underestimates of the cancer burden associated with coal.

Of the emissions of carcinogens in the life cycle inventory (inventory of all environmental flows) for coal-derived power, 94% were emitted to water, 6% to air, and 0.03% were to soil, mainly consisting of arsenic and cadmium (note: these do not sum to 100% due to rounding).<sup>25</sup> This number is not included in our total cost accounting to avoid double counting since these emissions may be responsible for health effects observed in mining communities.

### Mining and community health

A suite of studies of county-level mortality rates from 1979–2004 by Hendryx found that all-cause mortality rates,<sup>62</sup> lung cancer mortality rates,<sup>60</sup> and mortality from heart, respiratory, and kidney disease<sup>17</sup> were highest in heavy coal mining areas of Appalachia, less so in light coal mining areas, lesser still in noncoal mining areas in Appalachia, and lowest in noncoal mining areas outside of Appalachia. Another study performed by Hendryx and Ahern<sup>18</sup> found that self-reports revealed elevated rates of lung, cardiovascular and kidney diseases, and diabetes and hypertension in coal-mining areas. Yet, another study found that for pregnant women, residing in coal mining areas of West Virginia posed an independent risk for low birth weight (LBW) infants, raising the odds of an LBW infant by 16% relative to women residing in counties without coal mining.<sup>63</sup> LBW and preterm births are elevated,<sup>64</sup> and children born with extreme LBW fare worse than do children with normal birth weights in almost all neurological assessments;<sup>65</sup> as adults, they have more chronic diseases, including hypertension and diabetes mellitus.<sup>66</sup> Poor birth outcomes are especially elevated in areas with MTR mining as compared with areas with other forms of mining.<sup>67</sup> MTR mining has increased in the areas studied, and is occurring close to population centers.<sup>62</sup>

The estimated excess mortality found in coal mining areas is translated into monetary costs using the VSL approach. For the years 1997–2005, excess age-adjusted mortality rates in coal mining areas of Appalachia compared to national rates



**Figure 3.** Areas of highest biological diversity in the continental United States. Source: The Nature Conservancy, Arlington, VA. (In color in *Annals* online.)

outside Appalachia translates to 10,923 excess deaths every year, with 2,347 excess deaths every year after, adjusting for other socio-economic factors, including smoking rates, obesity, poverty, and access to health care. These socio-economic factors were statistically significantly worse in coal-mining areas.<sup>18,62,68</sup>

Using the VSL of \$7.5 million,<sup>20</sup> the unadjusted mortality rate, and the estimate that 91% of coal during these years was used for electricity,<sup>2</sup> this translates to a total cost of \$74.6 billion, or 4.36¢/kWh. In contrast, the authors calculated the direct (monetary value of mining industry jobs, including employees and proprietors), indirect (suppliers and others connected to the coal industry), and induced (ripple or multiplier effects throughout the economies) economic benefits of coal mining to Appalachia, and estimated the benefits to be \$8.08 billion in 2005 US\$.

### Ecological impacts

Appalachia is a biologically and geologically rich region, known for its variety and striking beauty. There is loss and degradation of habitat from MTR;

impacts on plants and wildlife (species losses and species impacted) from land and water contamination, and acid rain deposition and altered stream conductivity; and the contributions of deforestation and soil disruption to climate change.<sup>16,20</sup>

Globally, the rich biodiversity of Appalachian headwater streams is second only to the tropics.<sup>69</sup> For example, the southern Appalachian mountains harbor the greatest diversity of salamanders globally, with 18% of the known species world-wide (Fig. 3).<sup>69</sup>

### Imperiled aquatic ecosystems

Existence of viable aquatic communities in valley fill permit sites was first elucidated in court testimony leading to the “Haden decision.”<sup>70</sup> An interagency study of 30 streams in MTR mining-permit areas focused on the upper, unmapped reaches of headwater streams in West Virginia and Kentucky.<sup>71</sup> In performing this study, the researchers identified 71 genera of aquatic insects belonging to 41 families within eight insect orders. The most widely distributed taxa in 175 samples were found in abundance in 30 streams in five areas slated to undergo MTR.

Electrical conductivity (a measure of the concentration of ions) is used as one indicator of stream health.<sup>72</sup> The EPA recommends that stream conductivity not exceed 500 microsiemens per cm ( $\mu\text{S}/\text{cm}$ ). In areas with the most intense mining, in which 92% of the watershed had been mined, a recent study revealed levels of 1,100  $\mu\text{S}/\text{cm}$ .<sup>72</sup>

Meanwhile, even levels below 500  $\mu\text{S}/\text{cm}$  were shown to significantly affect the abundance and composition of macroinvertebrates, such as mayflies and caddis flies.<sup>73</sup> “Sharp declines” were found in some stream invertebrates where only 1% of the watershed had been mined.<sup>74,75</sup>

Semivoltine aquatic insects (e.g., many stoneflies and dragonflies)—those that require multiple years in the larval stage of development—were encountered in watersheds as small as 10–50 acres. While many of these streams become dry during the late summer months, they continue to harbor permanent resident taxonomic groups capable of withstanding summer dry conditions. Salamanders, the top predatory vertebrates in these fishless headwater streams, depend on permanent streams for their existence.

Mussels are a sensitive indicator species of stream health. Waste from surface mines in Virginia and Tennessee running off into the Clinch and Powell Rivers are overwhelming and killing these filter feeders, and the populations of mussels in these rivers has declined dramatically. Decreases in such filter feeders also affect the quality of drinking water downstream.<sup>76</sup>

In addition, stream dwelling larval stages of aquatic insects are impossible to identify to the species level without trapping adults or rearing larvae to adults.<sup>77</sup> However, no studies of adult stages are conducted for mining-permit applications.

The view that—because there are so many small streams and brooks in the Appalachians—destroying a portion represents a minor threat to biodiversity is contrary to the science. As the planet’s second-oldest mountain range, geologically recent processes in Appalachia in the Pleistocene epoch (from 2.5 million to 12,000 years ago) have created conditions for diversification, resulting in one of the U.S. biodiversity “hotspots” (Fig. 3).

Thus, burying an entire 2,000 hectare watershed, including the mainstream and tributaries, is likely to eliminate species of multiple taxa found only in Appalachia.

Researchers have concluded that many unknown species of aquatic insects have likely been buried under valley fills and affected by chemically contaminated waterways. Today’s Appalachian coal mining is undeniably resulting in loss of aquatic species, many of which will never be known. Much more study is indicated to appreciate the full spectrum of the ecological effects of MTR mining.<sup>78</sup>

### *Transport*

There are direct hazards from transport of coal. People in mining communities report that road hazards and dust levels are intense. In many cases dust is so thick that it coats the skin, and the walls and furniture in homes.<sup>41</sup> This dust presents an additional burden in terms of respiratory and cardiovascular disease, some of which may have been captured by Hendryx and colleagues.<sup>17–19,60,62,67,68,79</sup>

With 70% of U.S. rail traffic devoted to transporting coal, there are strains on the railroad cars and lines, and (lost) opportunity costs, given the great need for public transport throughout the nation.<sup>20</sup>

The NRC report<sup>20</sup> estimated the number of railroad fatalities by multiplying the proportion of revenue-ton miles (the movement of one ton of revenue-generating commodity over one mile) of commercial freight activity on domestic railroads accounted for by coal, by the number of public fatalities on freight railroads (in 2007); then multiplied by the proportion of transported coal used for electricity generation. The number of coal-related fatalities was multiplied by the VSL to estimate the total costs of fatal accidents in coal transportation. A total of 246 people were killed in rail accidents during coal transportation; 241 of these were members of the public and five of these were occupational fatalities. The deaths to the public add an additional cost of \$1.8 billion, or 0.09¢/kWh.

### *Social and employment impacts*

In Appalachia, as levels of mining increase, so do poverty rates and unemployment rates, while educational attainment rates and household income levels decline.<sup>19</sup>

While coal production has been steadily increasing (from 1973 to 2006), the number of employees at the mines increased dramatically from 1973 to 1979, then decreased to levels below 1973 employment levels.<sup>27</sup> Between 1985 and 2005 employment in the Appalachian coal mining industry declined by 56% due to increases in mechanization for MTR and

other surface mining.<sup>19,27</sup> There are 6,300 MTR and surface mining jobs in West Virginia, representing 0.7–0.8% of the state labor force.<sup>2</sup> Coal companies are also employing more people through temporary mining agencies and populations are shifting: between 1995 and 2000 coal-mining West Virginian counties experienced a net loss of 639 people to migration compared with a net migration gain of 422 people in nonmining counties.<sup>19,80</sup>

### Combustion

The next stage in the life cycle of coal is combustion to generate energy. Here we focus on coal-fired electricity-generating plants. The by-products of coal combustion include CO<sub>2</sub>, methane, particulates and oxides of nitrogen, oxides of sulfur, mercury, and a wide range of carcinogenic chemicals and heavy metals.<sup>20</sup>

**Long-range air pollutants and air quality.** Data from the U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID)<sup>81</sup> and National Emissions Inventory (NEI)<sup>82</sup> demonstrates that coal power is responsible for much of the U.S. power generation-related emissions of PM<sub>2.5</sub> (51%), NO<sub>x</sub> (35%), and SO<sub>2</sub> (85%). Along with primary emissions of the particulates, SO<sub>2</sub> and NO<sub>x</sub> contribute to increases in airborne particle concentrations through secondary transformation processes.<sup>20,21,83</sup>

Studies in New England<sup>84</sup> find that, although populations within a 30-mile radius of coal-fired power plants make up a small contribution to aggregate respiratory illness, on a per capita basis, the impacts on those nearby populations are two to five times greater than those living at a distance. Data in Kentucky suggest similar zones of high impact.

The direct health impacts of SO<sub>2</sub> include respiratory illnesses—wheezing and exacerbation of asthma, shortness of breath, nasal congestion, and pulmonary inflammation—plus heart arrhythmias, LBW, and increased risk of infant death.

The nitrogen-containing emissions (from burning all fossil fuels and from agriculture) cause damages through several pathways. When combined with volatile organic compounds, they can form not only particulates but also ground-level ozone (photochemical smog). Ozone itself is corrosive to the lining of the lungs, and also acts as a local heat-trapping gas.

**Epidemiology of air pollution.** Estimates of non-fatal health endpoints from coal-related pollutants vary, but are substantial—including 2,800 from lung cancer, 38,200 nonfatal heart attacks and tens of thousands of emergency room visits, hospitalizations, and lost work days.<sup>85</sup> A review<sup>83</sup> of the epidemiology of airborne particles documented that exposure to PM<sub>2.5</sub> is linked with all-cause premature mortality, cardiovascular and cardiopulmonary mortality, as well as respiratory illnesses, hospitalizations, respiratory and lung function symptoms, and school absences. Those exposed to a higher concentration of PM<sub>2.5</sub> were at higher risk.<sup>86</sup> Particulates are a cause of lung and heart disease, and premature death,<sup>83</sup> and increase hospitalization costs. Diabetes mellitus enhances the health impacts of particulates<sup>87</sup> and has been implicated in sudden infant death syndrome.<sup>88</sup> Pollution from two older coal-fired power plants in the U.S. Northeast was linked to approximately 70 deaths, tens of thousands of asthma attacks, and hundreds of thousands of episodes of upper respiratory illnesses annually.<sup>89</sup>

A reanalysis of a large U.S. cohort study on the health effects of air pollution, the Harvard Six Cities Study, by Schwartz *et al.*<sup>90</sup> used year-to-year changes in PM<sub>2.5</sub> concentrations instead of assigning each city a constant PM<sub>2.5</sub> concentration. To construct one composite estimate for mortality risk from PM<sub>2.5</sub>, the reanalysis also allowed for yearly lags in mortality effects from exposure to PM<sub>2.5</sub>, and revealed that the relative risk of mortality increases by 1.1 per 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> the year of death, but just 1.025 per 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> the year before death. This indicates that most of the increase in risk of mortality from PM<sub>2.5</sub> exposure occurs in the same year as the exposure. The reanalysis also found little evidence for a threshold, meaning that there may be no “safe” levels of PM<sub>2.5</sub> and that all levels of PM<sub>2.5</sub> pose a risk to human health.<sup>91</sup>

Thus, prevention strategies should be focused on continuous reduction of PM<sub>2.5</sub> rather than on peak days, and that air quality improvements will have effect almost immediately upon implementation. The U.S. EPA annual particulate concentration standard is set at 15.0 µg/m<sup>3</sup>, arguing that there is no evidence for harm below this level.<sup>92</sup> The results of the Schwartz *et al.*<sup>90</sup> study directly contradict this line of reasoning.



**Risk assessment.** The risk assessment performed by the NRC,<sup>20</sup> found aggregate damages of \$65 billion, including damages to public health, property, crops, forests, foregone recreation, and visibility due to emissions from coal-fired power plants of PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>x</sub>, volatile organic compounds, and ozone. The public health damages included mortality cases, bronchitis cases, asthma cases, hospital admissions related to respiratory, cardiac, asthma, coronary obstructive pulmonary disease, and ischemic heart disease problems, and emergency room visits related to asthma. On a plant-by-plant basis after being normalized to electricity produced by each plant, this was 3.2 ¢/kWh. Plant-by-plant estimates of the damages ranged from 1.9 ¢/kWh to 12 ¢/kWh. Plant-to-plant variation was largely due to controls on the plant, characteristics of the coal, and the population downwind of the plant. Emissions of SO<sub>2</sub> were the most damaging of the pollutants affecting air quality, and 99% of this was due to SO<sub>2</sub> in the particle form.<sup>20</sup> The NRC study found that over 90% of the damages due to air quality are from PM<sub>2.5</sub>-related mortality, which implies that these damages included approximately 8,158 excess mortality cases.<sup>20</sup> For the state of Kentucky alone, for each ton of SO<sub>2</sub> removed from the stack, the NRC (2009)<sup>20</sup> calculated a public health savings of \$5,800. Removing the close to 500,000 tons emitted in Kentucky would save over \$2.85 billion annually. The life cycle analysis found that damages from air quality public health impacts, monetized using methods from Externe<sup>26</sup> are approximately \$70.5 billion, which is roughly in line with this number.

The NRC's estimate is likely an underestimate, since the NRC used the concentration-response curve from Pope and Dockery,<sup>83</sup> which provides a low estimate for increases in mortality risk with increases in PM<sub>2.5</sub> exposure and is an outlier when compared to other studies examining the PM<sub>2.5</sub>-mortality relationship.<sup>6,87</sup> Had they used the result of the more recent study by Schwartz *et al.*,<sup>90</sup> which was used in a similar study by Levy *et al.*,<sup>21</sup> or the number from Dockery *et al.*,<sup>93</sup> the value they calculated would have been approximately three times higher,<sup>20</sup> therefore implying 24,475 excess deaths in 2005, with a cost of \$187.5 billion, or 9.3¢/kWh. As the Schwartz *et al.* study is more recent, uses elaborate statistical techniques to derive the concentration-response function for PM<sub>2.5</sub> and mortality, and is now widely accepted,<sup>21,94</sup> we use it

here to derive our best and high estimate, and the Pope and Dockery,<sup>83</sup> estimate to derive our low. Our best and high estimates for the damages due to air quality detriment impacts are both \$187.5 billion, and our low is \$65 billion. On a per-kWh basis, this is an average cost of 9.3 ¢/kWh with a low estimate of 3.2 ¢/kWh.

**Atmospheric nitrogen deposition.** In addition to the impacts to air quality and public health, nitrogen causes ecological harm via eutrophication. Eutrophication, caused by excess nitrogen inputs to coastal river zones, is the greatest source of water quality alteration in the United States and atmospheric deposition is one of the dominant sources of nitrogen inputs.<sup>95</sup> In an analysis by Jaworski *et al.*,<sup>95</sup> prepared for the EPA, 10 benchmark watersheds in the U.S. Northeast that flowed into the Atlantic coastal zone with good historical data were analyzed in conjunction with emissions data and reconstructed historical emissions. They found that the contribution to riverine nitrogen from nitrogen deposited from the air ranged from 36% to 80%, with a mean of 64%.

The other primary sources of nitrogen are fertilizers from point (e.g., river) discharges and nonpoint (e.g., agricultural land) sources, and other point sources including sewage from cities and farm animals, especially concentrated animal feeding operations.<sup>95</sup> Anthropogenic contributions of nitrogen are equal to the natural sources, doubling this form of fertilization of soils and water bodies.<sup>96</sup>

#### *Harmful algal blooms and dead zones*

Ocean and water changes are not usually associated with coal. But nitrogen deposition is a by-product of combustion and the EPA<sup>97</sup> has reached consensus on the link between aquatic eutrophication and harmful algal blooms (HABs), and concluded that nutrient over-fertilization is one of the reasons for their expansion in the United States and other nations. HABs are characterized by discolored water, dead and dying fish, and respiratory irritants in the air, and have impacts including illness and death, beach closures, and fish, bird, and mammal die-offs from exposure to toxins. Illnesses in humans include gastroenteritis, neurological deficits, respiratory illness, and diarrheic, paralytic, and neurotoxic shellfish poisonings.

N<sub>2</sub>O from land clearing is a heat-trapping gas<sup>38,42</sup> and adds to the nitrogen deposited in soils and water

bodies. The nitrogen is also a contributor to fresh and sea water acidification.<sup>98–100</sup> Other factors include the loss of wetlands that filter discharges.<sup>98–100</sup>

The economic losses from HABs are estimated to be over \$82 million/year in the United States, based on the most prominent episodes.<sup>101,102</sup> The full economic costs of HABs include public health impacts and health care costs, business interruptions of seafood and other allied industries (such as tourism and recreation, unemployment of fin- and shellfish fisherman and their families), and disruptions of international trade.<sup>98–100</sup>

The overfertilization of coastal zones worldwide has also led to over 350 “dead zones” with hypoxia, anoxia, and death of living marine organisms. Commercial and recreational fisheries in the Gulf of Mexico generate \$2.8 billion annually<sup>103</sup> and losses from the heavily eutrophied Gulf of Mexico dead zone put the regional economy at risk.

**Acid precipitation.** In addition to the health impacts of SO<sub>2</sub>, sulfates contribute to acid rain, decreased visibility, and have a greenhouse cooling influence.<sup>20</sup>

The long-term Hubbard Brook Ecosystem Study<sup>104</sup> has demonstrated that acid rain (from sulfates and nitrates) has taken a toll on stream and lake life, and soils and forests in the United States, primarily in the Northeast. The leaching of calcium from soils is widespread and, unfortunately, the recovery time is much longer than the time it takes for calcium to become depleted under acidic conditions.<sup>105</sup>

No monetized values of costs were found but a value for the benefits of improvements to the Adirondack State Park from acid rain legislation was produced by Resources for the Future, and found benefits ranging from \$336 million to \$1.1 billion per year.<sup>106</sup>

**Mercury.** Coal combustion in the U.S. releases approximately 48 tons of the neurotoxin mercury each year.<sup>54</sup> The most toxic form of mercury is methylmercury, and the primary route of human exposure is through consumption of fin- and shellfish containing bioaccumulated methylmercury.<sup>107</sup> Methylmercury exposure, both dietary and *in utero* through maternal consumption, is associated with neurological effects in infants and children, including delayed achievement of developmental milestones and poor results on neurobehavioral

tests—attention, fine motor function, language, visual-spatial abilities, and memory. Seafood consumption has caused 7% of women of childbearing age to exceed the mercury reference dose set by the EPA, and 45 states have issued fish consumption advisories.<sup>107</sup> Emission controls specific to mercury are not available, though 74–95% of emitted mercury is captured by existing emissions control equipment. More advanced technologies are being developed and tested.<sup>107</sup>

Direct costs of mercury emissions from coal-fired power plants causing mental retardation and lost productivity in the form of IQ detriments were estimated by Trasande *et al.*<sup>22,23</sup> to be \$361.2 million and \$1.625 billion, respectively, or 0.02¢/kWh and 0.1¢/kWh, respectively. Low-end estimates for these values are \$43.7 million and \$125 million, or 0.003¢/kWh and 0.007¢/kWh; high-end estimates for these values are \$3.3 billion and \$8.1 billion, or 0.19¢/kWh and 0.48¢/kWh.

There are also epidemiological studies suggesting an association between methylmercury exposure and cardiovascular disease.<sup>108</sup> Rice *et al.*<sup>109</sup> monetized the benefits of a 10% reduction in mercury emissions for both neurological development and cardiovascular health, accounting for uncertainty that the relationship between cardiovascular disease and methylmercury exposure is indeed causal. Applying these results for the cardiovascular benefits of a reduction in methylmercury to the 41% of total U.S. mercury emissions from coal<sup>22,23</sup> indicates costs of \$3.5 billion, with low and high estimates of \$0.2 billion and \$17.9 billion, or 0.2 ¢/kWh, with low and high estimates of 0.014 ¢/kWh and 1.05 ¢/kWh.

### Coal's contributions to climate change

The Intergovernmental Panel on Climate Change (IPCC) reported that annual global GHG emissions have—between 1970 and 2004—increased 70% to 49.0 Gt CO<sub>2</sub>-e/year.<sup>109</sup> The International Energy Agency's Reference Scenario estimates that worldwide CO<sub>2</sub> emissions will increase by 57% between 2005 and 2030, or 1.8% each year, to 41,905 Mt.<sup>1</sup> In the same time period, CO<sub>2</sub> emissions from coal-generated power are projected to increase 76.6% to 13,884 Mt.<sup>1</sup>

In 2005, coal was responsible for 82% of the U.S.'s GHG emissions from power generation.<sup>110</sup> In addition to direct stack emissions, there are methane



emissions from coal mines, on the order of 3% of the stack emissions.<sup>110</sup> There are also additional GHG emissions from the other uses of coal, approximately 139 Mt CO<sub>2</sub>.<sup>1</sup>

Particulate matter (black carbon or soot) is also a heat-trapping agent, absorbing solar radiation, and, even at great distances, decreasing reflectivity (albedo) by settling in snow and ice.<sup>111–113</sup> The contribution of particulates (from coal, diesel, and biomass burning) to climate change has, until recently, been underestimated. Though short-lived, the global warming potential per volume is 500 times that of CO<sub>2</sub>.<sup>111</sup>

### *Climate change*

Since the 1950s, the world ocean has accumulated 22 times as much heat as has the atmosphere,<sup>114</sup> and the pattern of warming is unmistakably attributable to the increase in GHGs.<sup>115</sup> Via this ocean repository and melting ice, global warming is changing the climate: causing warming, altered weather patterns, and sea level rise. Climate may change gradually or nonlinearly (in quantum jumps). The release of methane from Arctic seas and the changes in Earth's ice cover (thus albedo), are two potential amplifying feedbacks that could accelerate the rate of Earth's warming.

Just as we have underestimated the rate at which the climate would change, we have underestimated the pace of health and environmental impacts. Already the increases in asthma, heat waves, clusters of illnesses after heavy rain events and intense storms, and in the distribution of infectious diseases are apparent.<sup>116,117</sup> Moreover, the unfolding impacts of climate instability hold yet even more profound impacts for public health, as the changes threaten the natural life-supporting systems upon which we depend.

The EIA<sup>2</sup> estimated that 1.97 billion tons of CO<sub>2</sub> and 9.3 million tons CO<sub>2</sub>e of N<sub>2</sub>O were emitted directly from coal-fired power plants. Using the social cost of carbon, this resulted in a total cost of \$61.7 billion, or 3.06 ¢/kWh. Using the low and high estimates of the social cost of carbon results in cost of \$20.56 billion to \$205.6 billion, or 1.02 ¢/kWh to 10.2 ¢/kWh.

Black carbon emissions were also calculated using data from the EPA's eGRID database<sup>81</sup> on electricity produced from lignite. The low, mean, and high energy density values for lignite<sup>5</sup> was then used

to calculate the amount of lignite consumed. The Cooke *et al.*<sup>118</sup> emissions factor was used to estimate black carbon emissions based on lignite use and the Hansen *et al.*<sup>111</sup> global temperature potential was used to convert these emissions to CO<sub>2</sub>e. This resulted in an estimate of 1.5 million tons CO<sub>2</sub>e being emitted in 2008, with a value of \$45.2 million, or 0.002¢/kWh. Using our low and high estimates for the social cost of carbon and the high and low values for the energy density of lignite produced values of \$12.3 million to \$161.4 million, or 0.0006 ¢/kWh to 0.008¢/kWh.

One measure of the costs of climate change is the rising costs of extreme weather events, though these are also a function of and real estate and insurance values. Overall, the costs of weather-related disasters rose 10-fold from the 1980s to the 1990s (from an average of \$4 bn/year to \$40 bn/year) and jumped again in the past decade, reaching \$225 bn in 2005.<sup>119</sup> Worldwide, Munich Re—a company that insures insurers—reports that, in 2008, without Katrina-level disasters, weather-related “catastrophic losses” to the global economy were the third-highest in recorded history, topping \$200 billion, including \$45 billion in the United States.<sup>120</sup>

The total costs of climate change damages from coal-derived power, including black carbon, CO<sub>2</sub> and N<sub>2</sub>O emissions from combustion, land disturbance in MTR, and methane leakage from mines, is \$63.9 billion dollars, or 3.15 ¢/kWh, with low and high estimates of \$21.3 billion to \$215.9 billion, or 1.06 ¢/kWh to 10.71 ¢/kWh. A broad examination of the costs of climate change<sup>121</sup> projects global economic losses to between 5 and 20% of global gross domestic product (\$1.75–\$7 trillion in 2005 US\$); the higher figure based on the potential collapse of ecosystems, such as coral reefs and widespread forest and crop losses. With coal contributing at least one-third of the heat-trapping chemicals, these projections offer a sobering perspective on the evolving costs of coal; costs that can be projected to rise (linearly or nonlinearly) over time.

### **Carbon capture and storage**

Burning coal with CO<sub>2</sub> CCS in terrestrial, ocean, and deep ocean sediments are proposed methods of deriving “clean coal.” But—in addition to the control technique not altering the upstream life cycle costs—significant obstacles lie in the way, including the costs of construction of suitable plants

**Table 2.** MIT cost estimates for some representative CCS systems.<sup>5</sup>

		Subcritical PC		Supercritical PC		Ultra-supercritical PC		SC PC-Oxy	IGCC	
		No capture	Capture	No capture	Capture	No capture	Capture	Capture	No capture	Capture
CCS performance	Coal feed (kg/hr)	208,000	284,000	184,894	242,950	164,000	209,000	232,628	185,376	228,115
	CO <sub>2</sub> emitted (kg/hr)	466,000	63,600	414,903	54,518	369,000	46,800	52,202	415,983	51,198
	CO <sub>2</sub> captured at 90%, (kg/h)	0	573,000	0	490,662	0	422,000	46,981.7	0	460,782
	CO <sub>2</sub> emitted (g/kWh)	931	127	830	109	738	94	104	832	102
CCS costs	\$/kWh	1,280	2,230	1,330	2,140	1,360	2,090	1,900	1,430	1,890
	Total \$, assuming 500 MW plant	\$640,000,	\$1,115,000,	\$665,000,	\$1,070,000,	\$680,000,	\$1,045,000,	\$950,000,	\$715,000,	\$945,000,
	Inv. Charge ¢/kWh @ 15.1%	2.6	4.52	2.7	4.34	2.76	4.24	3.85	2.9	3.83
	Fuel ¢/kWh @ \$1.50/MMBtu	1.49	2.04	1.33	1.75	1.18	1.5	1.67	1.33	1.64
	O&M ¢/kWh	0.75	1.6	0.75	1.6	0.75	1.6	1.45	0.9	1.05
	COE ¢/kWh	4.84	8.16	4.78	7.69	4.69	7.34	8.98	5.13	6.52
	Cost of CO <sub>2</sub> avoided vs. same technology w/o capture (\$/ton)		41.3		40.4		41.1	30.3		19.3
	Cost of CO <sub>2</sub> avoided vs. supercritical technology w/o capture (\$/ton)		48.2		40.4		34.8	30.3		24
	Energy penalty		1,365,		1,313,		1,274,		1,230,	
			384,615		996,128		390,244		553,038	

and underground storage facilities, and the “energy penalty” requiring that coal consumption per unit of energy produced by the power plant increase by 25–40% depending on the technologies used.<sup>4,42</sup>

Retrofitting old plants—the largest source of CO<sub>2</sub> in the United States—may exact an even larger energy penalty. The energy penalty means that more coal is needed to produce the same quantity of electricity, necessitating more mining, processing, and transporting of coal and resulting in a larger waste stream to produce the same amount of electricity. Coal-fired plants would still require locally polluting diesel trucks to deliver the coal, and generate CCW ponds that can contaminate ground water. Given current siting patterns, such impacts often fall disproportionately on economically disadvantaged communities. The energy penalty combined with other increased costs of operating a CCS plant would nearly double the cost of generating electricity from that plant, depending on the technology used (see Table 2).<sup>5</sup>

The U.S. Department of Energy estimates that an underground volume of 30,000 km<sup>2</sup> will be needed per year to reduce the CO<sub>2</sub> emissions from coal by 20% by 2050 (the total land mass of the continental U.S. (48 states) is 9,158,960 km<sup>2</sup>).<sup>122</sup>

The safety and ensurability of scaling up the storage of the billion tons of CO<sub>2</sub> generated each year into the foreseeable future are unknown. Extrapolating from localized experiments, injecting fractions of the volumes that will have to be stored to make a significant difference in emissions, is fraught with numerous assumptions. Bringing CCS to scale raises additional risks, in terms of pressures underground. In addition to this, according to the U.S. Government Accountability Office (2008) there are regulatory, legal and liability uncertainties, and there is “significant cost of retrofitting existing plants that are single largest source of CO<sub>2</sub> emissions in the United States” (p. 7).<sup>123</sup>

**Health and environmental risks of CCS**

The Special IPCC Report on Carbon Dioxide Capture and Storage<sup>42</sup> lists the following concerns for CCS in underground terrestrial sites:

1. Storing compressed and liquefied CO<sub>2</sub> underground can acidify saline aquifers (akin to ocean acidification) and leach heavy metals, such as arsenic and lead, into ground water.<sup>42</sup>
2. Acidification of ground water increases fluid-rock interactions that enhance calcite dissolution and solubility, and can lead to fractures in

limestone ( $\text{CaCO}_3$ ) and subsequent releases of  $\text{CO}_2$  in high concentrations.<sup>124</sup>

3. Increased pressures may cause leaks and releases from previously drilled (often unmapped) pathways.
4. Increased pressures could destabilize underground faults and lead to earthquakes.
5. Large leaks and releases of concentrated  $\text{CO}_2$  are toxic to plants and animals.<sup>42</sup>
  - a. The 2006 Mammoth Mountain, CA release left dead stands of trees.<sup>124</sup>
6. Microbial communities may be altered, with release of other gases.<sup>42</sup>

The figures in Table 2 represent costs for new construction. Costs for retrofits (where CCS is installed on an active plant) and rebuilds (where CCS is installed on an active plant and the combustion technology is upgraded) are highly uncertain because they are extremely dependent on site conditions and precisely what technology the coal plant is upgraded to.<sup>5</sup> It does appear that complete rebuilds are more economically attractive than retrofits, and that “carbon-capture ready” plants are not economically desirable to build.<sup>5</sup>

### Subsidies

In Kentucky, coal brings in an estimated \$528 million in state revenues, but is responsible for \$643 million in state expenditures. The net impact, therefore, is a loss of \$115 million to the state of Kentucky.<sup>126</sup> These figures do not include costs of health care, lost productivity, water treatment for siltation and water infrastructure, limited development potential due to poor air quality, and social expenditures associated with declines in employment and related economic hardships of coal-field communities.<sup>126</sup>

The U.S. Federal Government provides subsidies for electricity and mining activities, and these have been tallied by both the EIA and the Environmental Law Institute.<sup>2,127,128</sup> The EIA estimate is \$3.17 billion of subsidies in 2007, or 0.16¢/kWh, and the Environmental Law Institute estimate is \$5.37 billion for 2007, or 0.27¢/kWh.

### Abandoned mine lands

Abandoned mine lands (AML) are those lands and waters negatively impacted by surface coal mining and left inadequately reclaimed or abandoned prior to August 3, 1977.<sup>129</sup> There are over 1,700 old aban-



**Figure 4.** Current high-priority abandoned mine land reclamation sites from Alabama to Pennsylvania.<sup>129</sup> (In color in *Animals* online.) Source: Hope Childers, Wheeling Jesuit University.

doned mines in Pennsylvania, alone.<sup>14</sup> In some—like that in Centralia, PA—fires burn for decades, emitting carbon monoxide, and other fumes. The ground above others can open, and several people die each year falling into them. Still others flood and lead to contaminated ground water. Previous coal mining communities lie in the shadow of these disturbed areas. Officials in Pennsylvania estimate that it will take \$15 billion over six decades to clean Pennsylvania’s abandoned mines.

Since the passage of the Surface Mining Control and Reclamation Act of 1977, active mining operations have been required to pay fees into the Abandoned Mine Reclamation Fund that are then used to finance reclamation of these AMLs.<sup>129</sup> Despite the more than \$7.4 billion that has been collected as of September 30, 2005, there is a growing backlog of unfunded projects.<sup>51</sup> Data on the number and monetary value of unfunded AML projects remaining at the end of 2007 for the nation were collected directly from the Abandoned Mine Land Inventory System<sup>129</sup> and amounted to \$8.8 billion 2008 US\$, or 0.44¢/kWh (Fig. 4).

### Results

The tabulation of the externalities in total and converted to 2008 US\$ is given in Table 3 and normalized to cents per kWh of coal-generated electricity

**Table 3. The complete costs of coal as reviewed in this report in 2008 US\$.**

	Monetized estimates from literature (2008 US\$)			Monetized life cycle assessment results (2008 US\$)	
	Low	Best	High	IPCC 2007, U.S. Hard Coal	U.S. Hard Coal Eco-indicator
	Land disturbance	\$54,311,510	\$162,934,529	\$3,349,209,766	
Methane emissions from mines	\$684,084,928	\$2,052,254,783	\$6,840,849,276	\$2,188,192, 405	
Carcinogens (mostly to water from waste)					\$11,775,544, 263
Public health burden of communities in Appalachia	\$74,612,823,575	\$74,612,823,575	\$74,612,823,575		
Fatalities in the public due to coal transport	\$1,807,500,000	\$1,807,500,000	\$1,807,500,000		
Emissions of air pollutants from combustion	\$65,094,911,734	\$187,473,345,794	\$187,473,345,794		\$71,011,655, 364
Lost productivity from mercury emissions	\$125,000,000	\$1,625,000,000	\$8,125,000,000		
Excess mental retardation cases from mercury emissions	\$43,750,000	\$361,250,000	\$3,250,000,000		
Excess cardiovascular disease from mercury emissions	\$246,000,000	\$3,536,250,000	\$17,937,500,000		
Climate damages from combustion emissions of CO <sub>2</sub> and N <sub>2</sub> O	\$20,559,709,242	\$61,679,127,726	\$205,597,092,419.52	\$70,442,466, 509	
Climate damages from combustion emissions of black carbon	\$12,346,127	\$45,186,823	\$161,381,512.28	\$3,739,876, 478	
Environmental Law Institute estimate 2007			\$5,373, 963,368		
EIA 2007	\$3,177,964,157	\$3,177, 964,157			
AMLs	\$8,775,282,692	\$8,775, 282,692	\$8,775, 282,692		
Climate total	\$21,310,451,806	\$63,939,503,861	\$215,948,532,974		
Total	\$175,193,683,964	\$345,308,920,080	\$523,303,948,403		

A 2010 Clean Air Task Force<sup>56</sup> (CATF) report, with Abt Associates consulting, lists 13,000 premature deaths due to air pollution from all electricity generation in 2010, a decrease in their estimates from previous years. They attribute the drop to 105 scrubbers installed since 2005, the year in which we based our calculations. We were pleased to see improvements reported in air quality and health outcomes. There is, however, considerable uncertainty regarding the actual numbers. Using the epidemiology from the “Six Cities Study” implies up to 34,000 premature deaths in 2010. Thus, our figures are mid-range while those of the CATF represent the most conservative of estimates.

in Table 4. Our best estimate for the externalities related to coal is \$345.3 billion (range: \$175.2 bn to \$523.3 bn). On a per-kWh basis this is 17.84¢/kWh, ranging from 9.42 ¢/kWh to 26.89 ¢/kWh.

**Limitations of this analysis**

While we have based this analysis on the best available data that are used by a wide range of organizations, this review is limited by the omission of

many environmental, community, mental health, and economic impacts that are not easily quantifiable. Another limitation is the placing of numbers on impacts that are difficult to quantify or monetize, including the VSL, a crude estimate of the benefits of reducing the number of deaths used by economists, and the social cost of carbon, based on the evolving impacts of climate change. We have included ranges, reflecting the numerous sets of data and studies in this field (all of which have their own

**Table 4.** Total costs of coal normalized to kWh of electricity produced.

	Monetized estimates from literature in ¢/kWh of electricity (2008 US\$)			Monetized life cycle assessment results in ¢/kWh of electricity (2008 US\$)	
	Low	Best	High	IPCC 2007, U.S. Hard Coal	U.S. Hard Coal Eco-indicator
Land disturbance	0.00	0.01	0.17		
Methane emissions from mines	0.03	0.08	0.34	0.11	
Carcinogens (mostly to water from waste)					0.60
Public health burden of communities in Appalachia	4.36	4.36	4.36		
Fatalities in the public due to coal transport	0.09	0.09	0.09		
Emissions of air pollutants from combustion	3.23	9.31	9.31		3.59
Lost productivity from mercury emissions	0.01	0.10	0.48		
Excess mental retardation cases from mercury emissions	0.00	0.02	0.19		
Excess cardiovascular disease from mercury emissions	0.01	0.21	1.05		
Climate damage from combustion emissions of CO <sub>2</sub> and N <sub>2</sub> O	1.02	3.06	10.20	3.56	
Climate damages from combustion emissions of black carbon	0.00	0.00	0.01	0.19	
Environmental Law Institute estimate 2007			0.27		
EIA 2007	0.16	0.16			
AMLs	0.44	0.44	0.44		
Climate total	1.06	3.15	10.7	3.75	1.54
Total	9.36	17.84	26.89		

uncertainties), varying assumptions in data sets and studies, and uncertainties about future impacts and the costs to society.

Some of the issues raised apply only to the region discussed. Decreased tourism in Appalachia, for example, affects regional economies; but may not affect the overall economy of the United States, as tourists may choose other destinations.

Studies in Australian coal mining communities illustrate the cycle of economic boom during construction and operation, the economic and worker decoupling from the fortunes of the mines; then the eventual closing.<sup>130</sup> Such communities experience high levels of depression and poverty, and increases in assaults (particularly sexual assaults), motor vehicle accidents, and crimes against

property, until the culture shifts to allow for development of secondary industries. Additional evidence documents that mining-dependent economies tend to be weak economies,<sup>131</sup> and weak economic conditions in turn are powerful predictors of social and health disadvantages.<sup>130,132</sup>

Some values are also difficult to interpret, given the multiple baselines against which they must be compared. In assessing the “marginal” costs of environmental damages, we have assumed the diverse, pristine, hardwood forest that still constitutes the majority of the beautiful rich and rolling hills that make up the Appalachian Mountain range.

Ecological and health economic analyses are also affected by the discount rate used in such evaluations. Discount rates are of great value in assessing the worth of commodities that deteriorate over time. But they are of questionable value in assessing ecological, life-supporting systems that have value if they are sustained. Ecological economists might consider employing a negative discount rate—or an accrual rate—in assessing the true impacts of environmental degradation and the value of sustainability.

Finally, the costs reported here do not include a wide range of opportunity costs, including lost opportunities to construct wind farms and solar power plants, begin manufacture of wind turbines and solar technologies, develop technologies for the smart grid and transmission, and for economic and business development unrelated to the energy sector.

## Conclusions

The electricity derived from coal is an integral part of our daily lives. However, coal carries a heavy burden. The yearly and cumulative costs stemming from the aerosolized, solid, and water pollutants associated with the mining, processing, transport, and combustion of coal affect individuals, families, communities, ecological integrity, and the global climate. The economic implications go far beyond the prices we pay for electricity.

Our comprehensive review finds that the best estimate for the total economically quantifiable costs, based on a conservative weighting of many of the study findings, amount to some \$345.3 billion, adding close to 17.8¢/kWh of electricity generated from coal. The low estimate is \$175 billion, or over 9¢/kWh, while the true monetizable costs could be as much as the upper bounds of \$523.3 billion,

adding close to 26.89¢/kWh. These and the more difficult to quantify externalities are borne by the general public.

Still these figures do not represent the full societal and environmental burden of coal. In quantifying the damages, we have omitted the impacts of toxic chemicals and heavy metals on ecological systems and diverse plants and animals; some ill-health endpoints (morbidity) aside from mortality related to air pollutants released through coal combustion that are still not captured; the direct risks and hazards posed by sludge, slurry, and CCW impoundments; the full contributions of nitrogen deposition to eutrophication of fresh and coastal sea water; the prolonged impacts of acid rain and acid mine drainage; many of the long-term impacts on the physical and mental health of those living in coal-field regions and nearby MTR sites; some of the health impacts and climate forcing due to increased tropospheric ozone formation; and the full assessment of impacts due to an increasingly unstable climate.

The true ecological and health costs of coal are thus far greater than the numbers suggest. Accounting for the many external costs over the life cycle for coal-derived electricity conservatively doubles to triples the price of coal per kWh of electricity generated.

Our analysis also suggests that the proposed measure to address one of the emissions—CO<sub>2</sub>, via CCS—is costly and carries numerous health and environmental risks, which would be multiplied if CCS were deployed on a wide scale. The combination of new technologies and the “energy penalty” will, conservatively, almost double the costs to operate the utility plants. In addition, questions about the reserves of economically recoverable coal in the United States carry implications for future investments into coal-related infrastructure.

Public policies, including the Clean Air Act and New Source Performance Review, are in place to help control these externalities; however, the actual impacts and damages remain substantial. These costs must be accounted for in formulating public policies and for guiding private sector practices, including project financing and insurance underwriting of coal-fired plants with and without CCS.

## Recommendations

1. Comprehensive comparative analyses of life cycle costs of all electricity generation

technologies and practices are needed to guide the development of future energy policies.

2. Begin phasing out coal and phasing in cleanly powered smart grids, using place-appropriate alternative energy sources.
3. A healthy energy future can include electric vehicles, plugged into cleanly powered smart grids; and healthy cities initiatives, including green buildings, roof-top gardens, public transport, and smart growth.
4. Alternative industrial and farming policies are needed for coal-field regions, to support the manufacture and installation of solar, wind, small-scale hydro, and smart grid technologies. Rural electric co-ops can help in meeting consumer demands.
5. We must end MTR mining, reclaim all MTR sites and abandoned mine lands, and ensure that local water sources are safe for consumption.
6. Funds are needed for clean enterprises, reclamation, and water treatment.
7. Fund-generating methods include:
  - a. maintaining revenues from the workers' compensation coal tax;
  - b. increasing coal severance tax rates;
  - c. increasing fees on coal haul trucks and trains;
  - d. reforming the structure of credits and taxes to remove misaligned incentives;
  - e. reforming federal and state subsidies to incentivize clean technology infrastructure.
8. To transform our energy infrastructure, we must realign federal and state rules, regulations, and rewards to stimulate manufacturing of and markets for clean and efficient energy systems. Such a transformation would be beneficial for our health, for the environment, for sustained economic health, and would contribute to stabilizing the global climate.

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## Conflicts of interest

The authors declare no conflicts of interest.

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# **Wind Turbine Sound and Health Effects An Expert Panel Review**

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# Acronyms and Abbreviations

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$\mu\text{Pa}$	microPascal
ACOEM	American College of Occupational and Environmental Medicine
ANSI	American National Standards Institute
AWEA	American Wind Energy Association
ASHA	American Speech-Language-Hearing Association
CanWEA	Canadian Wind Energy Association
dB	decibel
dBA	decibel (on an A-weighted scale)
DNL	day-night-level
DSM-IV-TR	<i>Diagnostic and Statistical Manual of Mental Disorders</i> , Fourth Edition
EPA	U.S. Environmental Protection Agency
FDA	Food and Drug Administration
FFT	Fast Fourier Transform
GI	gastrointestinal
HPA	Health Protection Agency
Hz	Hertz
IARC	International Agency for Research on Cancer
ICD-10	International Statistical Classification of Diseases and Related Health Problems, 10th Revision
IEC	International Engineering Consortium
ISO	International Organization for Standardization
Km	kilometer
kW	kilowatt
$L_{eq}$	equivalent level
LPALF	large pressure amplitude and low frequency
m/s	meters per second
$m/s^2$	meters per second squared
NIESH	National Institute of Environmental Health Sciences
NIHL	noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
$N/m^2$	Newtons per square meter
NRC	National Research Council
NTP	National Toxicology Program
ONAC	Office of Noise Abatement and Control
OSHA	Occupational Safety and Health Administration
Pa	Pascal
UK	United Kingdom
VAD	vibroacoustic disease
VVVD	vibratory vestibular disturbance
VEMP	vestibular evoked myogenic potential response
WHO	World Health Organization



# Executive Summary

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People have been harnessing the power of the wind for more than 5,000 years. Initially used widely for farm irrigation and millworks, today's modern wind turbines produce electricity in more than 70 countries. As of the end of 2008, there were approximately 120,800 megawatts of wind energy capacity installed around the world (Global Wind Energy Council, 2009).

Wind energy enjoys considerable public support, but it also has its detractors, who have publicized their concerns that the sounds emitted from wind turbines cause adverse health consequences.

In response to those concerns, the American and Canadian Wind Energy Associations (AWEA and CanWEA) established a scientific advisory panel in early 2009 to conduct a review of current literature available on the issue of perceived health effects of wind turbines. This multidisciplinary panel is comprised of medical doctors, audiologists, and acoustical professionals from the United States, Canada, Denmark, and the United Kingdom. The objective of the panel was to provide an authoritative reference document for legislators, regulators, and anyone who wants to make sense of the conflicting information about wind turbine sound.

The panel undertook extensive review, analysis, and discussion of the large body of peer-reviewed literature on sound and health effects in general, and on sound produced by wind turbines. Each panel member contributed a unique expertise in audiology, acoustics, otolaryngology, occupational/ environmental medicine, or public health. With a diversity of perspectives represented, the panel assessed the plausible biological effects of exposure to wind turbine sound.

Following review, analysis, and discussion of current knowledge, the panel reached consensus on the following conclusions:

- There is no evidence that the audible or sub-audible sounds emitted by wind turbines have any direct adverse physiological effects.
- The ground-borne vibrations from wind turbines are too weak to be detected by, or to affect, humans.
- The sounds emitted by wind turbines are not unique. There is no reason to believe, based on the levels and frequencies of the sounds and the panel's experience with sound exposures in occupational settings, that the sounds from wind turbines could plausibly have direct adverse health consequences.

## SECTION 1

# Introduction

---

The mission of the American Wind Energy Association (AWEA) is to promote the growth of wind power through advocacy, communication, and education. Similarly, the mission of the Canadian Wind Energy Association (CanWEA) is to promote the responsible and sustainable growth of wind power in Canada. Both organizations wish to take a proactive role in ensuring that wind energy projects are good neighbors to the communities that have embraced wind energy.

Together AWEA and CanWEA proposed to a number of independent groups that they examine the scientific validity of recent reports on the adverse health effects of wind turbine proximity. Such reports have raised public concern about wind turbine exposure. In the absence of declared commitment to such an effort from independent groups, the wind industry decided to be proactive and address the issue itself. In 2009, AWEA and CanWEA commissioned this report. They asked the authors to examine published scientific literature on possible adverse health effects resulting from exposure to wind turbines.

The objective of this report is to address health concerns associated with sounds from industrial-scale wind turbines. Inevitably, a report funded by an industry association will be subject to charges of bias and conflicts of interest. AWEA and CanWEA have minimized bias and conflicts of interest to the greatest possible extent through selection of a distinguished panel of independent experts in acoustics, audiology, medicine, and public health. This report is the result of their efforts.

## 1.1 Expert Panelists

The experts listed below were asked to investigate and analyze existing literature and publish their findings in this report; their current positions and/or qualifications for inclusion are also provided.

- W. David Colby, M.D.: Chatham-Kent Medical Officer of Health (Acting); Associate Professor, Schulich School of Medicine & Dentistry, University of Western Ontario
- Robert Dobie, M.D.: Clinical Professor, University of Texas, San Antonio; Clinical Professor, University of California, Davis
- Geoff Leventhall, Ph.D.: Consultant in Noise Vibration and Acoustics, UK
- David M. Lipscomb, Ph.D.: President, Correct Service, Inc.
- Robert J. McCunney, M.D.: Research Scientist, Massachusetts Institute of Technology Department of Biological Engineering; Staff Physician, Massachusetts General Hospital Pulmonary Division; Harvard Medical School
- Michael T. Seilo, Ph.D.: Professor of Audiology, Western Washington University

- Bo Søndergaard, M.Sc. (Physics): Senior Consultant, Danish Electronics Light and Acoustics (DELTA)

Mark Bastasch, an acoustical engineer with the consulting firm of CH2M HILL, acted as technical advisor to the panel.

## 1.2 Report Terminology

Certain terms are used frequently throughout this report. Table 1-1 defines these terms. An understanding of the distinction between “sound” and “noise” may be particularly useful to the reader.

---

**TABLE 1-1**  
Definitions of Acoustical Terms

<b>Term</b>	<b>Definitions</b>
Sound	Describes wave-like variations in air pressure that occur at frequencies that can stimulate receptors in the inner ear and, if sufficiently powerful, be appreciated at a conscious level.
Noise	Implies the presence of sound but also implies a response to sound: noise is often defined as unwanted sound.
Ambient noise level	The composite of noise from all sources near and far. The normal or existing level of environmental noise at a given location.
Decibel (dB)	A unit describing the amplitude of sound, equal to 20 times the logarithm to the base 10 of the ratio of the measured pressure to the reference pressure, which is 20 micropascals (μPa).
A-weighted sound pressure level (dBA)	The sound pressure level in decibels as measured on a sound level meter using the A-weighted filter network. The A-weighted filter de-emphasizes the very low and very high frequency components of the sound in a manner similar to the frequency response of the human ear and correlates well with subjective reactions to noise.
Hertz (Hz)	A unit of measurement of frequency; the number of cycles per second of a periodic waveform.
Infrasound	According to the International Electrotechnical Commission's (IEC's) IEC 1994, infrasound is: Acoustic oscillations whose frequency is below the low-frequency limit of audible sound (about 16 Hz). However this definition is incomplete as infrasound at high enough levels is audible at frequencies below 16 Hz.  (IEC (1994): 60050-801:1994 International Electrotechnical Vocabulary - Chapter 801: Acoustics and electroacoustics).
Low-frequency sound	Sound in the frequency range that overlaps the higher infrasound frequencies and the lower audible frequencies, and is typically considered as 10 Hz to 200 Hz, but is not closely defined.

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Source: HPA, 2009.

# Methodology

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Three steps form the basis for this report: formation of an expert panel, review of literature directly related to wind turbines, and review of potential environmental exposures.

## 2.1 Formation of Expert Panel

The American and Canadian wind energy associations, AWEA and CanWEA, assembled a distinguished panel of independent experts to address concerns that the sounds emitted from wind turbines cause adverse health consequences.

The objective of the panel was to provide an authoritative reference document for the use of legislators, regulators, and people simply wanting to make sense of the conflicting information about wind turbine sound.

The panel represented expertise in audiology, acoustics, otolaryngology, occupational/environmental medicine, and public health. A series of conference calls were held among panel members to discuss literature and key health concerns that have been raised about wind turbines. The calls were followed by the development of a draft that was reviewed by other panel members. Throughout the follow-up period, literature was critically addressed.

## 2.2 Review of Literature Directly Related to Wind Turbines

The panel conducted a search of Pub Med under the heading “Wind Turbines and Health Effects” to research and address peer-reviewed literature. In addition, the panel conducted a search on “vibroacoustic disease.” The reference section identifies the peer and non-peer reviewed sources that were consulted by the panel.

## 2.3 Review of Potential Environmental Exposures

The panel conducted a review of potential environmental exposures associated with wind turbine operations, with a focus on low frequency sound, infrasound, and vibration.

## SECTION 3

# Overview and Discussion

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This section summarizes the results of the review and analysis conducted by the expert panel and responds to a number of key questions:

- How do wind turbine operations affect human auditory response?
- How do we determine the loudness and frequency of sound and its effects on the human ear?
- How do wind turbines produce sound?
- How is sound measured and tested?
- What is vibration?
- What type of exposure to wind turbines is more likely to be perceived by humans (low frequency sound, infrasound or vibration)?
- Can sounds in the low frequency range, most notably the infrasonic range, adversely affect human health? Even when such levels are below the average person's ability to hear them?
- How does the human vestibular system respond to sound?
- What are the potential adverse effects and health implications of sound exposure?
- What does scientific literature say about wind turbines, low frequency sound, and infrasound?

## 3.1 Wind Turbine Operation and Human Auditory Response to Sound

### 3.1.1 Overview

The normal operation of a wind turbine produces sound and vibration, arousing concern about potential health implications. This section addresses the fundamental principles associated with sound and vibration, sound measurement, and potential adverse health implications. Sound from a wind turbine arises from its mechanical operation and the turning of the blades.

### 3.1.2 The Human Ear and Sound

The human ear is capable of perceiving a wide range of sounds, from the high-pitched sounds of a bird song to the low-pitched sound of a bass guitar. Sounds are perceived based on their loudness (i.e., volume or sound pressure level) or pitch (i.e., tonal or frequency content). The standard unit of measure for sound pressure levels is the decibel (dB). The standard unit used to describe the tonal or frequency content is the Hertz (Hz), measured in cycles per second) – Appendix A provides more information on the fundamentals of sound. Customarily, the young, non-pathological ear can perceive sounds ranging from 20 Hz to 20,000 Hz. Appendix B provides more information on the human ear.

Frequencies below 20 Hz are commonly called “infrasound,” although the boundary between infrasound and low frequency sound is not rigid. Infrasound, at certain frequencies and at high levels, can be audible to some people. Low frequency sound is customarily referred to as that between 10 Hz and 200 Hz, but any definition is arbitrary to some degree. Low frequency sound is the subject of concern to some with respect to potential health implications.

TABLE 3-1  
TYPICAL SOUND PRESSURE LEVELS MEASURED IN THE ENVIRONMENT AND  
INDUSTRY

Noise Source At a Given Distance	A-Weighted Sound Level in Decibels	Qualitative Description
Carrier deck jet operation	140	
	130	Pain threshold
Jet takeoff (200 feet)	120	
Auto horn (3 feet)	110	Maximum vocal effort
Jet takeoff (1000 feet)	100	
Shout (0.5 feet)		
N.Y. subway station	90	Very annoying
Heavy truck (50 feet)		Hearing damage (8-hour, continuous exposure)
Pneumatic drill (50 feet)	80	Annoying
Freight train (50 feet)	70 to 80	
Freeway traffic (50 feet)		
	70	Intrusive (Telephone use difficult)
Air conditioning unit (20 feet)	60	
Light auto traffic (50 feet)	50	Quiet
Living room	40	
Bedroom		
Library	30	Very quiet
Soft whisper (5 feet)		
Broadcasting/Recording studio	20	
	10	Just audible

Adapted from Table E, “Assessing and Mitigating Noise Impacts”, NY DEC, February 2001.

Table 3-1 shows sound pressure levels associated with common activities. Typically, environmental and occupational sound pressure levels are measured in decibels on an A-weighted scale (dBA). The A-weighted scale de-emphasizes the very low and very high frequency components of the sound in a manner similar to the frequency response of the human ear. For comparison, the sound from a wind turbine at distances between 1,000 and 2,000 feet is generally within 40 to 50 dBA.

Section 3.2 discusses the effects of exposure to wind turbine sound. Section 3.3 describes the potential adverse effects of sound exposure as well as the health implications.

### 3.1.3 Sound Produced by Wind Turbines

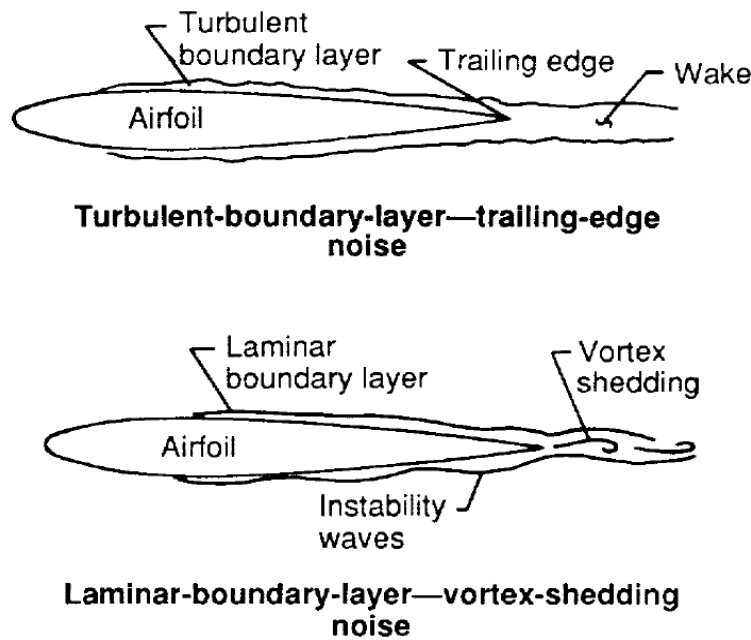
Wind turbine sound originates from either a mechanical or aerodynamic generation mechanism. Mechanical sound originates from the gearbox and control mechanisms. Standard noise control techniques typically are used to reduce mechanical sound. Mechanical noise is not typically the dominant source of noise from modern wind turbines (except for an occasional gear tone).

The aerodynamic noise is present at all frequencies, from the infrasound range over low frequency sound to the normal audible range and is the dominant source. The aerodynamic noise is generated by several mechanisms as is described below. The aerodynamic noise tends to be modulated in the mid frequency range, approximately 500 to 1,000 Hz.

Aerodynamic sound is produced by the rotation of the turbine blades through the air. A turbine blade shape is that of an airfoil. An airfoil is simply a structure with a shape that produces a lift force when air passes over it. Originally developed for aircraft, airfoil shapes have been adapted to provide the turning force for wind turbines by employing a shape which causes the air to travel more rapidly over the top of the airfoil than below it. The designs optimize efficiency by minimizing turbulence, which produces drag and noise. An aerodynamically efficient blade is a quiet one.

The aerodynamic sound from wind turbines is caused by the interaction of the turbine blade with the turbulence produced both adjacent to it (turbulent boundary layer) and in its near wake (see Figure 3-1) (Brooks et al., 1989). Turbulence depends on how fast the blade is moving through the air. A 100-meter-diameter blade, rotating once every three seconds, has a tip velocity of just over 100 meters per second. However, the speed reduces at positions closer to the centre of rotation (the wind turbine hub). The main determinants of the turbulence are the speed of the blade and the shape and dimensions of its cross-section.

FIGURE 3-1  
Sound Produced by Wind Turbine Flow



The following conclusions have been derived from the flow conditions shown in Figure 3-1 (Brooks et al., 1989):

- At high velocities for a given blade, turbulent boundary layers develop over much of the airfoil. Sound is produced when the turbulent boundary layer passes over the trailing edge.
- At lower velocities, mainly laminar boundary layers develop, leading to vortex shedding at the trailing edge.

Other factors in the production of aerodynamic sound include the following:

- When the angle of attack is not zero—in other words, the blade is tilted into the wind—flow separation can occur on the suction side near to the trailing edge, producing sound.
- At high angles of attack, large-scale separation may occur in a stall condition, leading to radiation of low frequency sound.
- A blunt trailing edge leads to vortex shedding and additional sound.
- The tip vortex contains highly turbulent flow.

Each of the above factors may contribute to wind turbine sound production. Measurements of the location of the sound source in wind turbines indicate that the dominant sound is produced along the blade—nearer to the tip end than to the hub. Reduction of turbulence sound can be facilitated through airfoil shape and by good maintenance. For example, surface irregularities resulting from damage or to accretion of additional material, may increase the sound.



Aerodynamic sound has been shown to be generated at higher levels during the downward motion of the blade (i.e., the three o'clock position). This results in a rise in level of approximately once per second for a typical three-bladed turbine. This periodic rise in level is also referred to as amplitude modulation, and as described above for a typical wind turbine, the modulation frequency is 1 Hz (once per second). In other words, the sound level rises and falls about once per second. The origin of this amplitude modulation is not fully understood. It was previously assumed that the modulation was caused when the blade went past the tower (given the tower disturbed the airflow), but it is now thought to be related to the difference in wind speed between the top and bottom of the rotation of a blade and directivity of the aerodynamic noise (Oerlemans and Schepers, 2009).

In other words, the result of aerodynamic modulation is a perceivable fluctuation in the sound level of approximately once per second. The frequency content of this fluctuating sound is typically between 500 Hz and 1,000 Hz, but can occur at higher and lower frequencies. That is, the sound pressure levels between approximately 500 and 1,000 Hz will rise and fall approximately once per second. It should be noted, however, that the magnitude of the amplitude modulation that is observed when standing beneath a tower does not always occur at greater separation distances. A study in the United Kingdom (UK) also showed that only four out of about 130 wind farms had a problem with aerodynamic modulation and three of these have been solved (Moorhouse et al., 2007).

In addition to the sound levels generated by the turbines, environmental factors affect the levels received at more distant locations. For example, warm air near the ground causes the turbine sound to curve upwards, away from the ground, which results in reduced sound levels, while warm air in a temperature inversion may cause the sound to curve down to the earth resulting in increased sound levels. Wind may also cause the sound level to be greater downwind of the turbine – that is, if the wind is blowing from the source towards a receiver – or lower, if the wind is blowing from the receiver to the source. Most modeling techniques, when properly implemented, account for moderate inversions and downwind conditions. Attenuation (reduction) of sound can also be influenced by barriers, ground surface conditions, shrubbery and trees, among other things.

Predictions of the sound level at varying distances from the turbine are based on turbine sound power levels. These turbine sound power levels are determined through standardized measurement methods.

### 3.1.4 Sound Measurement and Audiometric Testing

A sound level meter is a standard tool used in the measurement of sound pressure levels. As described in Section 3.1.2, the standard unit of sound pressure level (i.e., volume) is dB and the standard unit used to describe the pitch or frequency is Hz (cycles per second). A sound level meter may use the A-weighting filter to adjust certain frequency ranges (those that humans detect poorly), resulting in a reading in dBA (decibels, A-weighted). Appendix C provides more information on the measurement of sound. The pitch or frequencies (sometimes referred to as sound level spectrum) can be quantified using a sound level meter that includes a frequency analyzer. Octave band, one-third octave band, and narrow band (such as Fast Fourier Transform, or FFT) are three common types of frequency analyzers.

Consider, for example, a routine audiometric test (hearing test) in which a person sits in a booth and wears headphones, through which sounds are transmitted to evaluate hearing. Outside the booth, a technician turns a dial which yields certain frequencies (for example, 125 Hz, a low-pitched sound, or 4,000 Hz, a high-pitched sound) and then the technician raises the volume of each frequency until the person recognizes the sound of each tone. This is a standard approach used to measure thresholds for many reasons, including noise-induced hearing loss (NIHL). As the technician raises the volume of the designated frequency, the sound level (in dB) is noted. People who need more than 25 dB at more than one frequency to hear the sound (ie loudness of the tone) are considered to have an abnormal test.

The effects of prolonged, high-level sound exposure on hearing have been determined through audiometric tests of workers in certain occupations. The studies have been published in major medical journals and subjected to the peer review process (see, for example, McCunney and Meyer, 2007). Studies of workers have also served as the scientific basis for regulations on noise in industry that are overseen by the Occupational Safety and Health Administration (OSHA). Workers in noise-intensive industries have been evaluated for NIHL and certain industries are known to be associated with high noise levels, such as aviation, construction, and areas of manufacturing such as canning. Multiyear worker studies suggest that prolonged exposure to high noise levels can adversely affect hearing. The levels considered sufficiently high to cause hearing loss are considerably higher than one could experience in the vicinity of wind turbines. For example, prolonged, unprotected high exposure to noise at levels greater than 90 dBA is a risk for hearing loss in occupational settings such that OSHA established this level for hearing protection. Sound levels from wind turbines do not approach these levels (50 dBA at a distance of 1,500 feet would be a conservative estimate for today's turbines). Although the issue of NIHL has rarely been raised in opposition to wind farms, it is important to note that the risk of NIHL is directly dependent on the intensity (sound level) and duration of noise exposure and therefore it is reasonable to conclude that there is no risk of NIHL from wind turbine sound. Such a conclusion is based on studies of workers exposed to noise and among whom risk of NIHL is not apparent at levels less than 75 dBA.

## 3.2 Sound Exposure from Wind Turbine Operation

This section addresses the questions of (1) whether sounds in the low frequency range, most notably the infrasonic range, adversely affect human health, and whether they do so even when such levels are below the average person's ability to hear them; (2) what we are referring to when we talk about vibration; and (3) how the human vestibular system responds to sound and disturbance.

### 3.2.1 Infrasound and Low-Frequency Sound

Infrasound and low frequency sound are addressed in some detail to offer perspective on publicized hypotheses that sound from a wind turbine may damage health even if the noise levels are below those associated with noise-induced hearing loss in industry. For example, it has been proposed that sounds that contain low frequency noise, most notably within the infrasonic level, can adversely affect health even when the levels are below the average person's ability to detect or hear them (Alves-Pereira and Branco, 2007b).

Comprehensive reviews of infrasound and its sources and measurement have been published (Berglund and Lindvall, 1995; Leventhall et al., 2003). Table 3-2 shows the sound pressure level, in decibels, of the corresponding frequency of infrasound and low frequency sound necessary for the sound to be heard by the average person (Leventhall et al., 2003).

TABLE 3-2  
Hearing Thresholds in the Infrasonic and Low Frequency Range

Frequency (Hz)	4	8	10	16	20	25	40	50	80	100	125	160	200
Sound pressure level (dB)	107	100	97	88	79	69	51	44	32	27	22	18	14

**NOTE:**

Average hearing thresholds (for young healthy people) in the infrasound (4 to 20 Hz) and low frequency region (10 to 200 Hz).

Source: Leventhall et al., 2003

As Table 3-2 indicates, at low frequencies, a much higher level sound is necessary for a sound to be heard in comparison to higher frequencies. For example, at 10 Hz, the sound must be at 97 dB to be audible. If this level occurred at the mid to high frequencies, which the ear detects effectively, it would be roughly equivalent to standing without hearing protection directly next to a power saw. Decibel for decibel, the low frequencies are much more difficult to detect than the high frequencies, as shown in the hearing threshold levels of Table 3-2.

Table 3-2 also shows that even sounds as low as 4 Hz can be heard if the levels are high enough (107 dB). However, levels from wind turbines at 4 Hz are more likely to be around 70 dB or lower, and therefore inaudible. Studies conducted to assess wind turbine noise have shown that wind turbine sound at typical distances does not exceed the hearing threshold and will not be audible below about 50 Hz (Hayes 2006b; Kamperman and James, 2008). The hearing threshold level at 50 Hz is 44 dB, as shown in Table 3-2. Recent work on evaluating a large number of noise sources between 10 Hz and 160 Hz suggests that wind turbine noise heard indoors at typical separation distances is modest on the scale of low frequency sound sources (Pedersen, 2008). The low levels of infrasound and low frequency sound from wind turbine operations have been confirmed by others (Jakobsen, 2004; van den Berg, 2004).

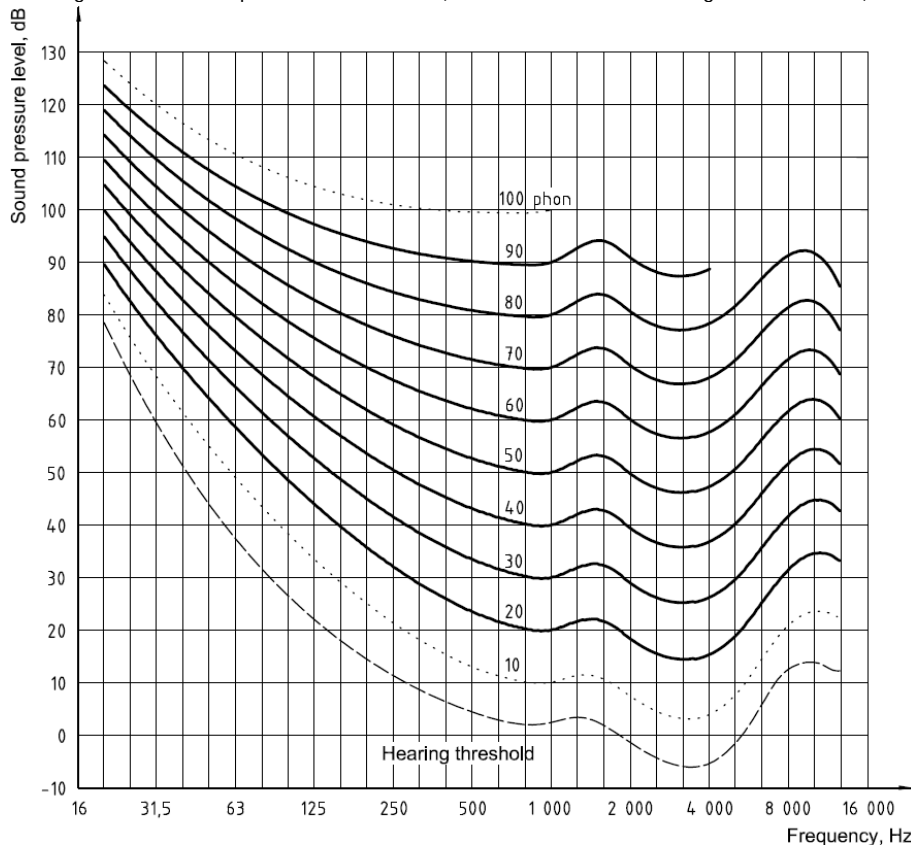
The low frequency sound associated with wind turbines has attracted attention recently since the A-weighting scale that is used for occupational and environmental regulatory compliance does not work well with sounds that have prominently low frequency components. Most environmental low frequency sound problems are caused by discrete tones (pitch or tones that are significantly higher in level (volume) than the neighboring frequencies); from, for example, an engine or compressor, not by continuous broadband sound. The high frequency sounds are assessed by the A-weighted measurement and, given their shorter wavelengths, are controlled more readily. Low frequency sounds may be irritating to some people and, in fact, some low frequency sound complaints prove impossible to resolve (Leventhall et al., 2003). This observation leads to a perception that there is something special, sinister, and harmful about low frequency sound. To the contrary, most external sound when heard indoors is biased towards low frequencies due to the efficient building attenuation of higher frequencies. One may recognize this when noise

from a neighbor's stereo is heard within their home – the bass notes are more pronounced than the higher frequency sounds. Any unwanted sound, whether high frequency or low frequency, can be irritating and stressful to some people.

Differences in how a low frequency sound and high frequency sound are perceived are well documented. Figure 3-2 shows that lower-frequency sounds typically need to be at a high sound pressure level (dB) to be heard. Figure 3-2 also demonstrates that as the frequency lowers, the audible range is compressed leading to a more rapid rise in loudness as the level changes in the lower frequencies. At 1,000 Hz, the whole range covers about 100 dB change in sound pressure level, while at 20 Hz the same range of loudness covers about 50 dB (note the contours displayed in Figure 3-2 are in terms of phons, a measure of equal loudness; for additional explanation on phons, the reader is referred to <http://www.sfu.ca/sonic-studio/handbook/Phon.html> [Truax, 1999]). As the annoyance of a given sound increases as loudness increases, there is also a more rapid growth of annoyance at low frequencies. However, there is no evidence for direct physiological effects from either infrasound or low frequency sound at the levels generated from wind turbines, indoors or outside. Effects may result from the sounds being audible, but these are similar to the effects from other audible sounds.

Low frequency sound and infrasound are further addressed in Section 3.3, Potential Adverse Effects of Exposure to Sound.

FIGURE 3-2  
Hearing Contours for Equal Loudness Level (International Standards Organization, 2003)



### 3.2.2 Vibration

Vibration, assumed to result from inaudible low frequency sounds, has been postulated to have a potential adverse effect on health. This section defines vibration, describes how it is measured, and cites studies that have addressed the risk of vibration on health.

Vibration refers to the way in which energy travels through solid material, whether steel, concrete in a bridge, the earth, the wall of a house or the human body. Vibration is distinguished from sound, which is energy flowing through gases (like air) or liquids (like water).

As higher frequency vibrations attenuate rapidly, it is low frequencies which are of potential concern to human health. When vibration is detected through the feet or through the seat, the focus of interest is the vibration of the surface with which one is in contact – for example, when travelling in a vehicle.

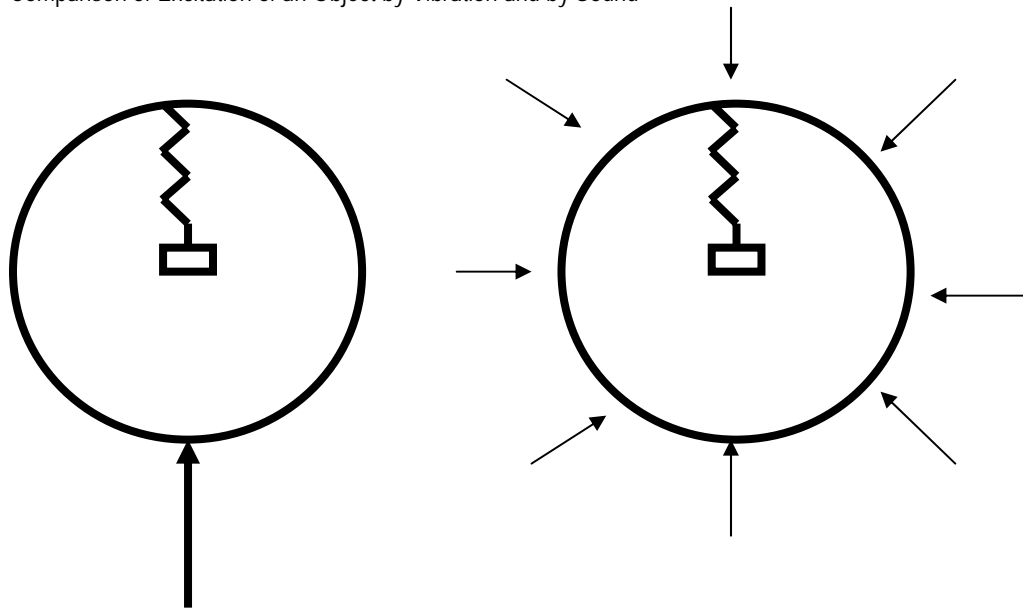
Vibration is often measured by the acceleration of the surface in meters per second, squared ( $m/s^2$ ), although other related units are used. Vibration can also be expressed in decibels, where the reference excitation level used in buildings is often  $10^{-5}m/s^2$  and the vibration level is  $20\log(A/10^{-5})$  dB, where A is the acceleration level in  $m/s^2$ .

The threshold of perception of vibration by humans is approximately  $0.01 m/s^2$ . If a frequency of excitation (vibration) corresponds with a resonant frequency of a system, then

excitation at the resonant frequency is greater than at other frequencies. However, excitation by sound is not the same as excitation by mechanical excitation applied at, say, the feet.

Figure 3-3 shows an object excited by point mechanical vibration and by sound. The object contains a resiliently suspended system. For example, if the object was the body, the suspended system might be the viscera (internal organs of the body). The left hand of the figure can be interpreted as the body vibrated by input to the feet. The vibration of the viscera will be maximum at the resonant frequency<sup>1</sup> of the suspended system, which, for viscera, is about 4 Hz. When excitation is by long wavelength low frequency sound waves, as shown at the right of the figure, not only is the force acting on the body much smaller than for vibration input, but, as the wavelength is much greater than the dimensions of the body, it is acting around the body in a compressive manner so that there is no resultant force on the suspended system and it does not vibrate or resonate.

FIGURE 3-3  
Comparison of Excitation of an Object by Vibration and by Sound



Unfortunately, this lack of effect has not been addressed by those who have suggested the mechanical vibration response of the body instead of the acoustic response as a potential health consequence. This oversight has led to inaccurate conclusions. For example, Dr. Nina Pierpont bases one of her key hypotheses for the cause of “wind turbine syndrome” on such an egregious error (Pierpont, 2009, pre-publication draft). Although not a recognized medical diagnosis, “wind turbine syndrome” has been raised as a concern for proposed projects—refer to Section 4.3 for more information.

Vibration of the body by sound at one of its resonant frequencies occurs only at very high sound levels and is not a factor in the perception of wind turbine noise. As will be discussed

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<sup>1</sup> A common example of resonance is pushing a child on a swing in which energy is given to the swing to maximize its oscillation.

below, the sound levels associated with wind turbines do not affect the vestibular or other balance systems.

### 3.2.3 Vestibular System

The vestibular system of the body plays a major role in maintaining a person's sense of balance and the stabilization of visual images. The vestibular system responds to pressure changes (sound pressure, i.e., decibels) at various frequencies. At high levels of exposure to low frequency sound, nausea and changes in respiration and blood pressure may occur. Studies have shown, however, that for these effects to occur, considerably high noise levels (greater than 140 dB, similar in sound level of a jet aircraft heard 80 feet away) are necessary (Berglund et al., 1996).

Head vibration resulting from low frequency sound has been suggested as a possible cause of a variety of symptoms that some hypothesize as being associated with wind turbines. In order to properly assess this hypothesis, this section addresses the human vestibular system. The "vestibular system" comprises the sense organs in the vestibular labyrinth, in which there are five tiny sensory organs: three semicircular canals that detect head rotation and two chalk-crystal-studded organs called otoliths (literally "ear-stones") that detect tilt and linear motion of the head. All five organs contain hair cells, like those in the cochlea, that convert motion into nerve impulses traveling to the brain in the vestibular nerve.

These organs evolved millions of years before the middle ear. Fish, for example, have no middle ear or cochlea but have a vestibular labyrinth nearly identical to ours (Baloh and Honrubia, 1979). The vestibular organs are specialized for stimulation by head position and movement, not by airborne sound. Each vestibular organ is firmly attached to the skull, to enable them to respond to the slightest head movement. In contrast, the hair cells in the cochlea are not directly attached to the skull; they do not normally respond to head movement, but to movements of the inner ear fluids.

The otolith organs help fish hear low frequency sounds; even in primates, these organs will respond to head vibration (i.e., bone-conducted sound) at frequencies up to 500 Hz (Fernandez and Goldberg, 1976). These vibratory responses of the vestibular system can be elicited by *airborne* sounds, however, only when they are at a much higher level than normal hearing thresholds<sup>2</sup> (and much higher than levels associated with wind turbine exposure). Thus, they do not help us hear but appear to be vestiges of our evolutionary past.

The vestibular nerve sends information about head position and movement to centers in the brain that also receive input from the eyes and from stretch receptors in the neck, trunk, and

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<sup>2</sup> Young et al. (1977) found that neurons coming from the vestibular labyrinth of monkeys responded to head vibration at frequencies of 200-400 Hz, and at levels as low as 70 to 80 dB below gravitational force. However, these neurons could not respond to airborne sound at the same frequencies until levels exceeded 76 dB sound pressure level (SPL), which is at least 40 dB higher than the normal threshold of human hearing in this frequency range. Human eye movements respond to 100 Hz head vibration at levels 15 dB below audible levels (Todd et al., 2008a). This does not mean that the vestibular labyrinth is more sensitive than the cochlea to airborne sound, because the impedance-matching function of the middle ear allows the cochlea to respond to sounds that are 50-60 dB less intense than those necessary to cause detectable head vibration. Indeed, the same authors (Todd et al., 2008b) found that for airborne sound, responses from the cochlea could always be elicited by sounds that were below the threshold for vestibular responses. Similarly, Welgampola et al. (2003) found that thresholds for vestibular evoked myogenic potential response (VEMP) were higher than hearing thresholds and stated: "the difference between hearing thresholds and VEMP thresholds is much greater for air conducted sounds than for bone vibration." In other words, the vestigial vestibular response to sound is relatively sensitive to bone conduction, which involves vibration of the whole head, and much less sensitive to air conduction.

legs (these stretch receptors tell which muscles are contracted and which joints are flexed, and provide the “proprioceptive” sense of the body’s position and orientation in space). The brain integrates vestibular, visual, and proprioceptive inputs into a comprehensive analysis of the position and movement of the head and body, essential for the sense of balance, avoidance of falls, and keeping the eyes focused on relevant targets, even during movement.

Perception of the body’s position in space may also rely in part on input from receptors in abdominal organs (which can shift back and forth as the body tilts) and from pressure receptors in large blood vessels (blood pools in the legs when standing, then shifts back to the trunk when lying down). These “somatic graviceptors” (Mittelstaedt, 1996) could be activated by whole-body movement and possibly by structure-borne vibration, or by the blast of a powerful near explosion, but, as described in Section 4.3.2, it is unlikely that intra-abdominal and intra-thoracic organs and blood vessels could detect airborne sound like that created by wind turbines.

Trauma, toxins, age-related degeneration, and various ear diseases can cause disorders of the vestibular labyrinth. A labyrinth not functioning properly can cause a person to feel unsteady or even to fall. Since the semicircular canals of the ear normally detect head rotation (such as shaking the head to indicate “no”), one of the consequences of a dysfunctional canal is that a person may feel a “spinning” sensation. This reaction is described as vertigo, from the Latin word to turn. In normal conversation, words like vertigo and dizziness can be used in ambiguous ways and thus make careful interpretation of potential health claims problematic. “Dizzy,” for example, may mean true vertigo or unsteadiness, both of which may be symptoms of inner ear disease. A person who describes being “dizzy” may actually be experiencing light-headedness, a fainting sensation, blurred vision, disorientation, or almost any other difficult-to-describe sensation in the head. The word “dizziness” can represent different sensations to each person, with a variety of causes. This can make the proper interpretation of research studies in which dizziness is evaluated a challenge to interpret.

Proper diagnostic testing to evaluate dizziness can reduce errors in misclassifying disease. The vestibular labyrinth, for example, can be tested for postural stability. Information from the semicircular canals is fed to the eye muscles to allow us to keep our eyes focused on a target; when the head moves; this “vestibulo-ocular reflex” is easily tested and can be impaired in vestibular disorders (Baloh and Honrubia, 1979).

### 3.3 Potential Adverse Effects of Exposure to Sound

Adverse effects of sound are directly dependent on the sound level; higher frequency sounds present a greater risk of an adverse effect than lower levels (see Table 3-2). Speech interference, hearing loss, and task interference occur at high sound levels. Softer sounds may be annoying or cause sleep disturbance in some people. At normal separation distances, wind turbines do not produce sound at levels that cause speech interference, but some people may find these sounds to be annoying.

#### 3.3.1 Speech Interference

It is common knowledge that conversation can be difficult in a noisy restaurant; the louder the background noise, the louder we talk and the harder it is to communicate. Average



levels of casual conversation at 1 meter (arm's length) are typically 50 to 60 dBA. People raise their voices – slightly and unconsciously at first – when ambient levels exceed 50 to 55 dBA, in order to keep speech levels slightly above background noise levels. Communication at arm's length requires conscious extra effort when levels exceed about 75 dBA. Above ambient levels of 80 to 85 dBA, people need to shout or get closer to converse (Pearsons et al., 1977; Webster, 1978). Levels below 45 dBA can be considered irrelevant with respect to speech interference.

### 3.3.2 Noise-Induced Hearing Loss

Very brief and intense sounds (above 130 dBA, such as in explosions) can cause instant cochlear damage and permanent hearing loss, but most occupational NIHL results from prolonged exposure to high noise levels between 90 and 105 dBA (McCunney and Meyer 2007). Regulatory (OSHA, 1983) and advisory (NIOSH, 1998) authorities in the U.S. concur that risk of NIHL begins at about 85 dBA, for an 8-hour day, over a 40-year career. Levels below 75 dBA do not pose a risk of NIHL. Thus, the sound levels associated with wind turbine operations would not cause NIHL because they are not high enough.

### 3.3.3 Task Interference

Suter (1991) reviewed the effects of noise on performance and behavior. Simple tasks may be unaffected even at levels well above 100 dBA, while more complex tasks can be disrupted by intermittent noise as low as 75 dBA. Speech sounds are usually more disruptive than nonspeech sounds. Levels below 70 dBA do not result in task interference.

### 3.3.4 Annoyance

Annoyance as a possible “effect” of wind turbine operations is discussed in detail in later sections of this report (Sections 3.4 and 4.1). In summary, annoyance is a subjective response that varies among people to many types of sounds. It is important to note that although annoyance may be a frustrating experience for people, it is not considered an adverse health effect or disease of any kind. Certain everyday sounds, such as a dripping faucet – barely audible – can be annoying. Annoyance cannot be predicted easily with a sound level meter. Noise from airports, road traffic, and other sources (including wind turbines) may annoy some people, and, as described in Section 4.1, the louder the noise, the more people may become annoyed.

### 3.3.5 Sleep Disturbance

The U.S. Environmental Protection Agency (EPA) document titled *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety* (1974) recommends that indoor day-night-level (DNL) not exceed 45 dBA. DNL is a 24-hour average that gives 10 dB extra weight to sounds occurring between 10p.m. and 7 a.m., on the assumption that during these sleep hours, levels above 35 dBA indoors may be disruptive.

### 3.3.6 Other Adverse Health Effects of Sound

At extremely high sound levels, such as those associated with explosions, the resulting sound pressure can injure any air-containing organ: not only the middle ear (eardrum

perforations are common) but also the lungs and intestines (Sasser et al., 2006). At the other extreme, any sound that is chronically annoying, including very soft sounds, may, for some people, create chronic stress, which can in turn lead to other health problems. On the other hand, many people become accustomed to regular exposure to noise or other potential stressors, and are no longer annoyed. The hypothesis that chronic noise exposure might lead to chronic health problems such as hypertension and heart disease has been the subject of hundreds of contradictory studies of highly variable quality, which will not be reviewed in this document. Other authors have reviewed this literature, and some of their conclusions are quoted below:

“It appears not likely that noise in industry can be a direct cause of general health problems..., except that the noise can create conditions of psychological stress...which can in turn cause physiological stress reactions...” (Kryter, 1980)

“Epidemiological evidence on noise exposure, blood pressure, and ischemic heart disease is still limited.” (Babisch, 2004), and “contradictory’ (Babisch, 1998), but “there is some evidence...of an increased risk in subjects who live in noisy areas with outdoor noise levels of greater than 65 - 70 dBA.” (Babisch, 2000)

“The present state of the art does not permit any definite conclusion to be drawn about the risk of hypertension.” (van Dijk, Ettema, and Zielhuis, 1987)

“At this point, the relationship between noise induced hearing loss and hypertension must be considered as possible but lacking sufficient evidence to draw causal associations.” (McCunney and Meyer, 2007)

### 3.3.7 Potential Health Effects of Vibration Exposure

People may experience vibration when some part of the body is in direct contact with a vibrating object. One example would be holding a chainsaw or pneumatic hammer in the hands. Another would be sitting in a bus, truck, or on heavy equipment such as a bulldozer. Chronic use of vibrating tools can cause “hand-arm vibration syndrome,” a vascular insufficiency condition characterized by numbness and tingling of the fingers, cold intolerance, “white-finger” attacks, and eventually even loss of fingers due to inadequate blood supply. OSHA does not set limits for vibration exposure, but the American National Standards Institute (ANSI) (2006) recommends that 8-hour workday exposures to hand-arm vibration (5 to 1400 Hz, summed over three orthogonal axes of movement) not exceed acceleration values of 2.5 m/s<sup>2</sup>.

Excessive whole-body vibration is clearly linked to low back pain (Wilder, Wasserman, and Wasserman, 2002) and may contribute to gastrointestinal and urinary disorders, although these associations are not well established. ANSI (1979) recommends 8-hour limits for whole-body vibration of 0.3 m/s<sup>2</sup>, for the body’s most sensitive frequency range of 4 to 8 Hz. This is about 30 times more intense than the weakest vibration that people can detect (0.01 m/s<sup>2</sup>).

Airborne sound can cause detectable body vibration, but this occurs only at very high levels – usually above sound pressure levels of 100 dB (unweighted) (Smith, 2002; Takahashi et al., 2005; Yamada et al., 1983). There is no scientific evidence to suggest that modern wind turbines cause perceptible vibration in homes or that there is an associated health risk.

### 3.4 Peer-Reviewed Literature Focusing on Wind Turbines, Low-Frequency Sound, and Infrasound

This section addresses the scientific review of the literature that has evaluated wind turbines, the annoyance effect, low frequency sound, and infrasound.

#### 3.4.1 Evaluation of Annoyance and Dose-Response Relationship of Wind Turbine Sound

To date, three studies in Europe have specifically evaluated potential health effects of people living in proximity to wind turbines (Pedersen and Persson Waye, 2004; Pedersen and Persson Waye, 2007; Pedersen et al., 2009). These studies have been primarily in Sweden and the Netherlands. Customarily, an eligible group of people are selected for possible participation in the study based on their location with respect to a wind turbine. Control groups have not been included in any of these reports.

In an article published in August 2009, investigators reported the results of their evaluation of 725 people in the Netherlands, who lived in the vicinity of wind turbines (Pedersen et al., 2009). The potential study population consisted of approximately 70,000 people living within 2.5 kilometers of a wind turbine at selected sites in the Netherlands. The objective of the study was to (1) assess the relationship between wind turbine sound levels at dwellings and the probability of noise annoyance, taking into account possible moderating factors, and (2) explore the possibility of generalizing a dose response relationship for wind turbine noise by comparing the results of the study with previous studies in Sweden.

Noise impact was quantified based on the relationship between the sound level (dose) and response with the latter measured as the proportion of people annoyed or highly annoyed by sound. Prior to this study, dose response curves had been modeled for wind turbines. Previous studies have noted different degrees of relationships between wind turbine sound levels and annoyance (Wolsink et al., 1993; Pedersen and Persson Waye, 2004; Pedersen and Persson Waye, 2007).

Subjective responses were obtained through a survey. The calculation of the sound levels (dose) in Sweden and the Netherlands were similar. A dose response relationship was observed between calculated A-weighted sound pressure levels and annoyance. Sounds from wind turbines were found to be more annoying than several other environmental sources at comparable sound levels. A strong correlation was also noted between noise annoyance and negative opinion of the impact of wind turbines on the landscape, a finding in earlier studies as well. The dominant quality of the sound was a swishing, the quality previously found to be the most annoying type.

The authors concluded that this study could be used for calculating a dose response curve for wind turbine sound and annoyance. The study results suggest that wind turbine sound is easily perceived and, compared with sound from other sources, is annoying to a small percentage of people (5 percent at 35 to 40 dBA).

In this study, the proportion of people who reported being annoyed by wind turbine noise was similar to merged data from two previous Swedish studies (Pederson and Persson

Waye, 2004; Pedersen and Persson Waye, 2007). About 5 percent of respondents were annoyed at noise levels between 35 to 40 dBA and 18 percent at 40 to 45 dBA.

Pedersen et al. also reported significant dose responses between wind turbine sound and self-reported annoyance (Pedersen and Persson Waye, 2004). High exposed individuals responded more (78 percent) than low exposed individuals (60 percent), which suggests that bias could have played a role in the final results.

An analysis of two cross-sectional socio-acoustic studies – one that addressed flat landscapes in mainly rural settings (Pedersen and Persson Waye, 2004) and another in different terrains (complex or flat) and different levels of urbanization (rural or suburban) (Pedersen and Persson Waye, 2007) – was performed (Pedersen, 2008). Approximately 10 percent of over 1000 people surveyed via a questionnaire reported being very annoyed at sound levels of 40 dB and greater. Attitude toward the visual impact of the wind turbines had the same effect on annoyance. Response to wind turbine noise was significantly related to exposure expressed as A-weighted sound pressure levels dB. Among those who could hear wind turbine sound, annoyance with wind turbine noise was highly correlated to the sound characteristics: swishing, whistling, resounding and pulsating/throbbing (Pedersen, 2008).

A similar study in Sweden evaluated 754 people living near one of seven sites where wind turbine power was greater than 500 kilowatt (kW) (Pedersen and Persson Waye, 2007). Annoyance was correlated with sound level and also with negative attitude toward the visual impact of the wind turbines. Note that none of these studies included a control group. Earlier field studies performed among people living in the vicinity of wind turbines showed a correlation between sound pressure level and noise annoyance; however, annoyance was also influenced by visual factors and attitudes toward the impact of the wind turbines on the landscape. Noise annoyance was noted at lower sound pressure levels than annoyance from traffic noise. Although some people may be affected by annoyance, there is no scientific evidence that noise at levels created by wind turbines could cause health problems (Pedersen and Högskolan, 2003).

### 3.4.2 Annoyance

A feeling described as “annoyance” can be associated with acoustic factors such as wind turbine noise. There is considerable variability, however, in how people become “annoyed” by environmental factors such as road construction and aviation noise, among others (Leventhall, 2004). Annoyance is clearly a subjective effect that will vary among people and circumstances. In extreme cases, sleep disturbance may occur. Wind speed at the hub height of a wind turbine at night may be up to twice as high as during the day and may lead to annoyance from the amplitude modulated sound of the wind turbine (van den Berg, 2003). However, in a study of 16 sites in 3 European countries, only a weak correlation was noted between sound pressure level and noise annoyance from wind turbines (Pedersen and Högskolan, 2003).

In a detailed comparison of the role of noise sensitivity in response to environmental noise around international airports in Sydney, London, and Amsterdam, it was shown that noise sensitivity increases one’s perception of annoyance independently of the level of noise exposure (van Kamp et al., 2004).

In a Swedish study, 84 out of 1,095 people living in the vicinity of a wind turbine in 12 geographical areas reported being fairly or very annoyed by wind turbines (Pedersen, 2008). It is important to note that no differences were reported among people who were “annoyed” in contrast to those who were not annoyed with respect to hearing impairment, diabetes, or cardiovascular disease. An earlier study in Sweden showed that the proportion of people “annoyed” by wind turbine sound is higher than for other sources of environmental noise at the same decibel level (Pedersen and Persson Waye, 2004).

### 3.4.3 Low-Frequency Sound and Infrasound

No scientific studies have specifically evaluated health effects from exposure to low frequency sound from wind turbines. Natural sources of low frequency sound include wind, rivers, and waterfalls in both audible and non-audible frequencies. Other sources include road traffic, aircraft, and industrial machinery. The most common source of infrasound is vehicular (National Toxicology Program, 2001).

Infrasound at a frequency of 20 Hz (the upper limit of infrasound) is not detectable at levels lower than 79 dB (Leventhall et al., 2003). Infrasound at 145 dB at 20 Hz and at 165 dB at 2 Hz can stimulate the auditory system and cause severe pain (Leventhall, 2006). These noise levels are substantially higher than any noise generated by wind turbines. The U.S. Food and Drug Administration (FDA) has approved the use of infrasound for therapeutic massage at 70 dB in the 8 to 14 Hz range (National Toxicology Program, 2001). In light of the FDA approval for this type of therapeutic use of infrasound, it is reasonable to conclude that exposure to infrasound in the 70 dB range is safe. According to a report of the National Research Council (NRC), low frequency sound is a concern for older wind turbines but not the modern type (National Research Council, 2007).

# Results

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This section discusses the results of the analysis presented in Section 3. Potential effects from infrasound, low frequency sound, and the fluctuating aerodynamic “swish” from turbine blades are examined. Proposed hypotheses between wind turbine sound and physiological effects in the form of vibroacoustic disease, “wind turbine syndrome,” and visceral vibratory vestibular disturbance are discussed.

## 4.1 Infrasound, Low-Frequency Sound, and Annoyance

Sound levels from wind turbines pose no risk of hearing loss or any other nonauditory effect. In fact, a recent review concluded that “Occupational noise-induced hearing damage does not occur below levels of 85 dBA.” (Ising and Kruppa, 2004) The levels of sound associated with wind turbine operations are considerably lower than industry levels associated with noise induced hearing loss.

However, some people attribute certain health problems to wind turbine exposure. To make sense of these assertions, one must consider not only the sound but the complex factors that may lead to the perception of “annoyance.” Most health complaints regarding wind turbines have centered on sound as the cause. There are two types of sounds from wind turbines: mechanical sound, which originates from the gearbox and control mechanisms, and the more dominant aerodynamical sound, which is present at all frequencies from the infrasound range over low frequency sound to the normal audible range.

Infrasound from natural sources (for example, ocean waves and wind) surrounds us and is below the audible threshold. The infrasound emitted from wind turbines is at a level of 50 to 70 dB, sometimes higher, but well below the audible threshold. There is a consensus among acoustic experts that the infrasound from wind turbines is of no consequence to health. One particular problem with many of these assertions about infrasound is that is that the term is often misused when the concerning sound is actually low frequency sound, not infrasound.

Under many conditions, low frequency sound below about 40 Hz cannot be distinguished from environmental background sound from the wind itself. Perceptible (meaning above both the background sound and the hearing threshold), low frequency sound can be produced by wind turbines under conditions of unusually turbulent wind conditions, but the actual sound level depends on the distance of the listener from the turbine, as the sound attenuates (falls off) with distance. The higher the frequency, the greater the sound attenuates with distance – Appendix D provides more information on the propagation of sound. The low frequency sound emitted by spinning wind turbines could possibly be annoying to some when winds are unusually turbulent, but there is no evidence that this level of sound could be harmful to health. If so, city dwelling would be impossible due to the similar levels of ambient sound levels normally present in urban environments. Nevertheless, a small number of people find city sound levels stressful.

It is not usually the low frequency nonfluctuating sound component, however, that provokes complaints about wind turbine sound. The fluctuating aerodynamic sound (swish) in the 500 to 1,000 Hz range occurs from the wind turbine blades disturbing the air, modulated as the blades rotate which changes the sound dispersion characteristics in an audible manner. This fluctuating aerodynamic sound is the cause of most sound complaints regarding wind turbines, as it is harder to become accustomed to fluctuating sound than to sound that does not fluctuate. However, this fluctuation does not always occur and a UK study showed that it had been a problem in only four out of 130 UK wind farms, and had been resolved in three of those (Moorhouse et al., 2007).

#### 4.1.1 Infrasound and Low-Frequency Sound

Infrasound occurs at frequencies less than 20 Hz. At low and inaudible levels, infrasound has been suggested as a cause of “wind turbine syndrome” and vibroacoustic disease (VAD)—refer to Section 4.2.1 for more information on VAD. For infrasound to be heard, high sound levels are necessary (see Section 3, Table 3-2). There is little risk of short term acute exposure to high levels of infrasound. In experiments related to the Apollo space program, subjects were exposed to between 120 and 140 dB without known harmful effects. High level infrasound is less harmful than the same high levels of sound in the normal audible frequency range.

High levels of low frequency sound can excite body vibrations (Leventhall, 2003). Early attention to low frequency sound was directed to the U.S. space program, studies from which suggested that 24-hour exposures to 120 to 130 dB are tolerable below 20 Hz, the upper limit of infrasound. Modern wind turbines produce sound that is assessed as infrasound at typical levels of 50 to 70 dB, below the hearing threshold at those frequencies (Jakobsen, 2004). Jakobsen concluded that infrasound from wind turbines does not present a health concern. Fluctuations of wind turbine sound, most notably the swish-swish sounds, are in the frequency range of 500 to 1,000 Hz, which is neither low frequency sound nor infrasound. The predominant sound from wind turbines, however, is often mischaracterized as infrasound and low frequency sound. Levels of infrasound near modern-scale wind farms are in general not perceptible to people. In the human body, the beat of the heart is at 1 to 2 Hz. Higher-frequency heart sounds measured externally to the body are in the low frequency range (27 to 35 dB at 20 to 40 Hz), although the strongest frequency is that of the heartbeat (Sakai, Feigen, and Luisada, 1971). Lung sounds, measured externally to the body are in the range of 5 to 35 dB at 150 to 600 Hz (Fiz et al., 2008). Schust (2004) has given a comprehensive review of the effects of high level low frequency sound, up to 100 Hz.

#### 4.1.2 Annoyance

Annoyance is a broad topic on which volumes have been written. Annoyance can be caused by constant amplitude and amplitude modulated sounds containing rumble (Bradley, 1994).

As the level of sound rises, an increasing number of those who hear it may become distressed, until eventually nearly everybody is affected, although to different degrees. This is a clear and easily understood process. However, what is not so clearly understood is that when the level of the sound reduces, so that very few people are troubled by it, there remain a small number who may be adversely affected. This occurs at all frequencies, although there seems to be more subjective variability at the lower frequencies. The effect of low

frequency sound on annoyance has recently been reviewed (Leventhall, 2004). The standard deviation of the hearing threshold is approximately 6 dB at low frequencies (Kurakata and Mizunami, 2008), so that about 2.5 percent of the population will have 12 dB more sensitive hearing than the average person. However, hearing sensitivity alone does not appear to be the deciding factor with respect to annoyance. For example, the same type of sound may elicit different reactions among people: one person might say “Yes, I can hear the sound, but it does not bother me,” while another may say, “The sound is impossible, it is ruining my life.” There is no evidence of harmful effects from the low levels of sound from wind turbines, as experienced by people in their homes. Studies have shown that peoples’ attitudes toward wind turbines may affect the level of annoyance that they report (Pedersen et al., 2009).

Some authors emphasize the psychological effects of sounds (Kalveram, 2000; Kalveram et al., 1999). In an evaluation of 25 people exposed to five different wind turbine sounds at 40 dB, ratings of “annoyance” were different among different types of wind turbine noise (Persson Waye and Öhrström, 2002).

None of the psycho-acoustic parameters could explain the difference in annoyance responses. Another study of more than 2,000 people suggested that personality traits play a role in the perception of annoyance to environmental issues such as sound (Persson et al., 2007). Annoyance originates from acoustical signals that are not compatible with, or that disturb, psychological functions, in particular, disturbance of current activities. Kalveram et al. (1999) suggest that the main function of noise annoyance is as a warning that fitness may be affected but that it causes little or no physiological effect. Protracted annoyance, however, may undermine coping and progress to stress related effects. It appears that this is the main mechanism for effects on the health of a small number of people from prolonged exposure to low levels of noise.

The main health effect of noise stress is disturbed sleep, which may lead to other consequences. Work with low frequencies has shown that an audible low frequency sound does not normally become objectionable until it is 10 to 15 dB above hearing threshold (Inukai et al., 2000; Yamada, 1980). An exception is when a listener has developed hostility to the noise source, so that annoyance commences at a lower level.

There is no evidence that sound at the levels from wind turbines as heard in residences will cause direct physiological effects. A small number of sensitive people, however, may be stressed by the sound and suffer sleep disturbances.

### 4.1.3 Other Aspects of Annoyance

Some people have concluded that they have health problems caused directly by wind turbines. In order to make sense of these complaints, we must consider not only the sound, but the complex factors culminating in annoyance.

There is a large body of medical literature on stress and psychoacoustics. Three factors that may be pertinent to a short discussion of wind turbine annoyance effects are the nocebo effect, sensory integration dysfunction and somatoform disorders.



#### 4.1.4 Nocebo Effect

The nocebo effect is an adverse outcome, a worsening of mental or physical health, based on fear or belief in adverse effects. This is the opposite of the well known placebo effect, where belief in positive effects of an intervention may produce positive results (Spiegel, 1997). Several factors appear to be associated with the nocebo phenomenon: expectations of adverse effects; conditioning from prior experiences; certain psychological characteristics such as anxiety, depression and the tendency to somatize (express psychological factors as physical symptoms; see below), and situational and contextual factors. A large range of reactions include hypervagotonia, manifested by idioventricular heart rhythm (a slow heart rate of 20 to 50 beats per minute resulting from an intrinsic pacemaker within the ventricles which takes over when normal sinoatrial node regulation is lost), drowsiness, nausea, fatigue, insomnia, headache, weakness, dizziness, gastrointestinal (GI) complaints and difficulty concentrating (Sadock and Sadock, 2005, p.2425). This array of symptoms is similar to the so-called “wind turbine syndrome” coined by Pierpont (2009, pre-publication draft). Yet these are all common symptoms in the general population and no evidence has been presented that such symptoms are more common in persons living near wind turbines. Nevertheless, the large volume of media coverage devoted to alleged adverse health effects of wind turbines understandably creates an anticipatory fear in some that they will experience adverse effects from wind turbines. Every person is suggestible to some degree. The resulting stress, fear, and hypervigilance may exacerbate or even create problems which would not otherwise exist. In this way, anti-wind farm activists may be creating with their publicity some of the problems that they describe.

#### 4.1.5 Somatoform Disorders

There are seven somatoform disorders in the Fourth Edition of *Diagnostic and Statistical Manual of Mental Disorders* (DSM-IV-TR) (American Psychiatric Association, 2000). Somatoform disorders are physical symptoms which reflect psychological states rather than arising from physical causes. One common somatoform disorder, Conversion Disorder, is the unconscious expression of stress and anxiety as one or more physical symptoms (Escobar and Canino, 1989). Common conversion symptoms are sensations of tingling or discomfort, fatigue, poorly localized abdominal pain, headaches, back or neck pain, weakness, loss of balance, hearing and visual abnormalities. The symptoms are not feigned and must be present for at least six months according to DSM-IV-TR and two years according to the International Statistical Classification of Diseases and Related Health Problems, 10th Revision (ICD-10) (WHO, 1993). ICD-10 specifies the symptoms as belonging to four groups: (1) Gastrointestinal (abdominal pain, nausea, bloating/gas/, bad taste in mouth/excessive tongue coating, vomiting/regurgitation, frequent/loose bowel movements); (2) Cardiovascular (breathlessness without exertion, chest pains); (3) Genitourinary (frequency or dysuria, unpleasant genital sensations, vaginal discharge), and (4) Skin and Pain (blotchiness or discoloration of the skin, pain in the limbs, extremities or joints, paresthesias). ICD-10 specifies that at least six symptoms must be present in two or more groups.

One feature of somatoform disorders is *somatosensory amplification*, a process in which a person learns to feel body sensations more acutely and may misinterpret the significance of those sensations by equating them with illness (Barsky, 1979). *Sensory integration dysfunction*

describes abnormal sensitivity to any or all sensory stimuli (sound, touch, light, smell, and taste). There is controversy among researchers and clinicians as to whether sensory integration problems exist as an independent entity or as components of a pervasive developmental disorder (Sadock and Sadock, 2005, p. 3135), but their presence can lead to overestimation of the likelihood of being ill (Sadock and Sadock, 2005, p. 1803). Sensory integration dysfunction as such is not listed in the DSM-IV-TR or in the ICD-10.

Day-to-day stressors and adverse life events provide multiple stimuli to which people respond, and that response is often somatic due to catecholamines and activation of the autonomic nervous system. This stress response can become conditioned as memory. There is some evidence that poor coping mechanisms (anger impulsivity, hostility, isolation, lack of confiding in others) are linked to physiological reactivity, which is associated with somatic sensation and amplification (Sadock and Sadock, 2005, p. 1806).

In summary, the similarities of common human stress responses and conversion symptoms to those described as “wind turbine syndrome” are striking. An annoyance factor to wind turbine sounds undoubtedly exists, to which there is a great deal of individual variability. Stress has multiple causes and is additive. Associated stress from annoyance, exacerbated by the rhetoric, fears, and negative publicity generated by the wind turbine controversy, may contribute to the reported symptoms described by some people living near rural wind turbines.

## 4.2 Infrasound, Low-frequency Sound and Disease

Some reports have suggested a link between low frequency sound from wind turbines and certain adverse health effects. A careful review of these reports, however, leads a critical reviewer to question the validity of the claims for a number of reasons, most notably (1) the level of sound exposure associated with the putative health effects, (2) the lack of diagnostic specificity associated with the health effects reported, and (3) the lack of a control group in the analysis.

### 4.2.1 Vibroacoustic Disease

Vibroacoustic disease (VAD) in the context of exposure of aircraft engine technicians to sound was defined by Portuguese researchers as a whole-body, multi-system entity, caused by chronic exposure to large pressure amplitude and low frequency (LPALF) sound (Alves-Pereira and Castelo Branco, 2007a; Alves-Pereira and Castelo Branco, 2007b; Alves-Pereira and Castelo Branco, 2007c; Alves-Pereira and Castelo Branco, 2007d). VAD, the primary feature of which is thickening of cardiovascular structures, such as cardiac muscle and blood vessels, was first noted among airplane technicians, military pilots, and disc jockeys (Maschke, 2004; Castelo Branco, 1999). Workers had been exposed to high levels for more than 10 years. There are no epidemiological studies that have evaluated risk of VAD from exposure to infrasound. The likelihood of such a risk, however, is remote in light of the much lower vibration levels in the body itself. Studies of workers with substantially higher exposure levels have not indicated a risk of VAD. VAD has been described as leading from initial respiratory infections, through pericardial thickening to severe and life-threatening illness such as stroke, myocardial infarction, and risk of malignancy (Alves-Pereira and Castelo Branco, 2007a).

## 4.2.2 High-Frequency Exposure

All of the exposures of subjects for whom the VAD concept was developed, were dominated by higher frequency sounds, a critical point since the frequency range claimed for VAD-inducing sound is much wider than the frequency range of exposures experienced by the aircraft technicians who were diagnosed with VAD (Castelo Branco, 1999). Originally, proponents of the VAD concept had proposed a “greater than 90 dB” criterion for VAD. However, now some claim that VAD will result from exposure to almost any level of infrasound and low frequency sound at any frequency below 500 Hz. This assertion is an extraordinary extrapolation given that the concept of VAD developed from observations that a technician, working around military aircraft on the ground, with engines operating, displayed disorientation (Castelo Branco, 1999). Sound levels near aircraft were very high. In an evaluation of typical engine spectra of carrier based combat aircraft operating on the ground, the spectra peaked at frequencies above 100 Hz with sound levels from 120 to 135 dB close to the aircraft (Smith, 2002). The levels drop considerably, however, into the low frequency region.

There is an enormous decibel difference between the sound exposure of aircraft technicians and the sound exposure of people who live near wind turbines. Animal experiments indicated that exposure levels necessary to cause VAD were 13 weeks of continuous exposure to approximately 100 dB of low frequency sound (Mendes et al., 2007). The exposure levels were at least 50 to 60 dB higher than wind turbine levels in the same frequency region (Hayes, 2006a).

## 4.2.3 Residential Exposure: A Case Series

Extrapolation of results from sound levels greater than 90 dB and at predominantly higher frequencies (greater than 100 Hz) to a risk of VAD from inaudible wind turbine sound levels of 40 to 50 dB in the infrasound region, is a new hypothesis. One investigator, for example, has claimed that wind turbines in residential areas produce acoustical environments that can lead to the development of VAD in nearby home-dwellers (Alves-Pereira and Castelo Branco, 2007a).

This claim is based on comparison of only two infrasound exposures. The first is for a family which has experienced a range of health problems and which also complained of disturbances from low frequency sound. The second is for a family which lived near four wind turbines, about which they have become anxious (Alves-Pereira and Castelo Branco, 2007a; Alves-Pereira and Castelo Branco, 2007b).

The first family (Family F), was exposed to low levels of infrasound consisting of about 50 dB at 8 Hz and 10 Hz from a grain terminal about 3 kilometers (km) away and additional sources of low frequency sound, including a nearer railway line and road. The second family (Family R) lives in a rural area and was described as exposed to infrasound levels of about 55 dB to 60 dB at 8 Hz to 16 Hz. These exposures are well below the hearing threshold and not uncommon in urban areas. Neither the frequency nor volume of the sound exposures experienced by Families F or R are unusual. Exposure to infrasound (< 20 Hz) did not exceed 50 dB.

#### 4.2.3.1 Family F—Exposure to Low Levels of Infrasound

Family F has a long history of poor health and a 10-year-old boy was diagnosed with VAD due to exposure to infrasound from the grain terminal (Alves-Pereira and Castelo Branco, 2007a; Castelo Branco et al., 2004). However, the infrasound levels are well below hearing threshold and are typical of urban infrasound, which occurs widely and to which many people are exposed.

According to the authors, the main effect of VAD was demonstrated by the 10-year-old boy in the family, as pericardial thickening.<sup>3</sup> However, the boy has a history of poor health of unknown etiology (Castelo Branco et al., 2004). Castelo Branco (1999) has defined pericardial thickening as an indicator of VAD and assumes that the presence of pericardial thickening in the boy from Family F must be an effect of VAD, caused by exposure to the low-level, low frequency sound from the grain terminal. This assumption excludes other possible causes of pericardial thickening, including viral infection, tuberculosis, irradiation, hemodialysis, neoplasia with pericardial infiltration, bacterial, fungal, or parasitic infections, inflammation after myocardial infarction, asbestosis, and autoimmune diseases. The authors did not exclude these other possible causes of pericardial thickening.

#### 4.2.3.2 Family R—Proximity to Turbines and Anxiety

Family R, living close to the wind turbines, has low frequency sound exposure similar to that of Family F. The family does not have symptoms of VAD, but it was claimed that “Family R. will also develop VAD should they choose to remain in their home.” (Alves-Pereira and Castelo Branco, 2007b). In light of the absence of literature of cohort and case control studies, this bold statement seems to be unsubstantiated by available scientific literature.

### 4.2.4 Critique

It appears that Families F and R were self-selected complainants. Conclusions derived by Alves-Pereira and Castelo Branco (2007b) have been based only on the poor health and the sound exposure of Family F, using this single exposure as a measure of potential harmful effects for others. There has been no attempt at an epidemiological study.

Alves-Pereira and Castelo Branco claim that exposure at home is more significant than exposure at work because of the longer periods of exposure (Alves-Pereira and Castelo Branco, 2007e). Because an approximate 50 dB difference occurs between the exposure from wind turbines and the exposure that induced VAD (Hayes, 2006a), it will take  $10^5$  years (100,000 years) for the wind turbine dose to equal that of one year of the higher level sound.

Among published scientific literature, this description of the two families is known as a case series, which are of virtually no value in understanding potential *causal associations* between exposure to a potential hazard (i.e., low frequency sound) and a potential health effect (i.e., vibroacoustic disease). Case reports have value but primarily in generating hypotheses to test in other studies such as large groups of people or in case control studies. The latter type of study can systematically evaluate people with pericardial thickening who live near wind turbines in comparison to people with pericardial thickening who do not live

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<sup>3</sup> Pericardial thickening is unusual thickening of the protective sac (pericardium) which surrounds the heart. For example, see <http://www.emedicine.com/radio/topic191.htm>.

near wind turbines. Case reports need to be confirmed in larger studies, most notably cohort studies and case-control studies, before definitive cause and effect assertions can be drawn. The reports of the two families do not provide persuasive scientific evidence of a link between wind turbine sound and pericardial thickening.

Wind turbines produce low levels of infrasound and low frequency sound, yet there is no credible scientific evidence that these levels are harmful. If the human body is affected by low, sub-threshold sound levels, a unique and not yet discovered receptor mechanism of extraordinary sensitivity to sound is necessary – a mechanism which can distinguish between the normal, relatively high-level “sound” inherent in the human body<sup>4</sup> and excitation by external, low-level sound. Essential epidemiological studies of the potential effects of exposure at low sound levels at low frequencies have not been conducted. Until the fuzziness is clarified, and a receptor mechanism revealed, no reliance can be placed on the case reports that the low levels of infrasound and low frequency sound are a cause of vibroacoustic disease.<sup>5</sup>

The attribution of dangerous properties to low levels of infrasound continues unproven, as it has been for the past 40 years. No foundation has been demonstrated for the new hypothesis that exposure to sub-threshold, low levels of infrasound will lead to vibroacoustic disease. Indeed, human evolution has occurred in the presence of natural infrasound.

## 4.3 Wind Turbine Syndrome

“Wind turbine syndrome” as promoted by Pierpont (2009, pre-publication draft) appears to be based on the following two hypotheses:

1. Low levels of airborne infrasound from wind turbines, at 1 to 2 Hz, directly affect the vestibular system.
2. Low levels of airborne infrasound from wind turbines at 4 to 8 Hz enter the lungs via the mouth and then vibrate the diaphragm, which transmits vibration to the viscera, or internal organs of the body.

The combined effect of these infrasound frequencies sends confusing information to the position and motion detectors of the body, which in turn leads to a range of disturbing symptoms.

### 4.3.1 Evaluation of Infrasound on the Vestibular System

Consider the first hypothesis. The support for this hypothesis is a report apparently misunderstood to mean that the vestibular system is more sensitive than the cochlea to low levels of both sound and vibration (Todd et al., 2008a). The Todd report is concerned with vibration input to the mastoid area of the skull, and the corresponding detection of these vibrations by the cochlea and vestibular system. The lowest frequency used was 100 Hz,

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<sup>4</sup> Body sounds are often used for diagnosis. For example see Gross, V., A. Dittmar, T. Penzel, F., Schüttler, and P. von Wichert.. (2000): "The Relationship between Normal Lung Sounds, Age, and Gender." *American Journal of Respiratory and Critical Care Medicine*. Volume 162, Number 3: 905 - 909.

<sup>5</sup> This statement should not be interpreted as a criticism of the work of the VAD Group with aircraft technicians at high noise levels.

considerably higher than the upper limit of the infrasound frequency (20 Hz). The report does not address air-conducted sound or infrasound, which according to Pierpont excites the vestibular system by airborne sound and by skull vibration. This source does not support Pierpont's hypothesis and does not demonstrate the points that she is trying to make.

There is no credible scientific evidence that low levels of wind turbine sound at 1 to 2 Hz will directly affect the vestibular system. In fact, it is likely that the sound will be lost in the natural infrasonic background sound of the body. The second hypothesis is equally unsupported with appropriate scientific investigations. The body is a noisy system at low frequencies. In addition to the beating heart at a frequency of 1 to 2 Hz, the body emits sounds from blood circulation, bowels, stomach, muscle contraction, and other internal sources. Body sounds can be detected externally to the body by the stethoscope.

### 4.3.2 Evaluation of Infrasound on Internal organs

It is well known that one source of sound may mask the effect of another similar source. If an external sound is detected within the body in the presence of internally generated sounds, the external sound must produce a greater effect in the body than the internal sounds. The skin is very reflective at higher frequencies, although the reflectivity reduces at lower frequencies (Katz, 2000). Investigations at very low frequencies show a reduction of about 30 dB from external to internal sound in the body of a sheep (Peters et al., 1993). These results suggest an attenuation (reduction) of low frequency sound by the body before the low frequency sound reaches the internal organs.

Low-level sounds from outside the body do not cause a high enough excitation within the body to exceed the internal body sounds. Pierpont refers to papers from Takahashi and colleagues on vibration excitation of the head by high levels of external sound (over 100 dB). However, these papers state that response of the head at frequencies below 20 Hz was not measurable due to the masking effect of internal body vibration (Takahashi et al., 2005; Takahashi et al., 1999). When measuring chest resonant vibration caused by external sounds, the internal vibration masks resonance for external sounds below 80 dB excitation level (Leventhall, 2006). Thus, the second hypothesis also fails.

To recruit subjects for her study, Pierpont sent out a general call for anybody believing their health had been adversely affected by wind turbines. She asked respondents to contact her for a telephone interview. The case series results for ten families (37 subjects) are presented in Pierpont (2009, pre-publication draft). Symptoms included sleep disturbance, headache, tinnitus, ear pressure, vertigo, nausea, visual blurring, tachycardia, irritability, concentration, memory, panic attacks, internal pulsation, and quivering. This type of study is known as a case series. A case series is of limited, if any, value in evaluating causal connections between an environmental exposure (in this case, sound) and a designated health effect (so called "wind turbine syndrome"). This particular case series is substantially limited by selection bias, in which people who already think that they have been affected by wind turbines "self select" to participate in the case series. This approach introduces a significant bias in the results, especially in the absence of a control group who do not live in proximity of a wind turbine. The results of this case series are at best hypothesis-generating activities that do not provide support for a causal link between wind turbine sound and so-called "wind turbine syndrome."

However, these so called “wind turbine syndrome” symptoms are not new and have been published previously in the context of “annoyance” to environmental sounds (Nagai et al., 1989; Møller and Lydolf, 2002; Mirowska and Mroz, 2000). The following symptoms are based on the experience of noise sufferers extending over a number of years: distraction, dizziness, eye strain, fatigue, feeling vibration, headache, insomnia, muscle spasm, nausea, nose bleeds, palpitations, pressure in the ears or head, skin burns, stress, and tension (Leventhall, 2002).

The symptoms are common in cases of extreme and persistent annoyance, leading to stress responses in the affected individual and may also result from severe tinnitus, when there is no external sound. The symptoms are exhibited by a small proportion of sensitive persons and may be alleviated by a course of psychotherapy, aimed at desensitization from the sound (Leventhall et al., 2008). The similarity between the symptoms of noise annoyance and those of “wind turbine syndrome” indicates that this “diagnosis” is not a pathophysiological effect, but is an example of the well-known stress effects of exposure to noise, as displayed by a small proportion of the population. These effects are familiar to environmental noise control officers and other “on the ground” professionals.

“Wind turbine syndrome,” not a recognized medical diagnosis, is essentially reflective of symptoms associated with noise annoyance and is an unnecessary and confusing addition to the vocabulary on noise. This syndrome is not a recognized diagnosis in the medical community. There are no unique symptoms or combinations of symptoms that would lead to a specific pattern of this hypothesized disorder. The collective symptoms in some people exposed to wind turbines are more likely associated with annoyance to low sound levels.

## 4.4 Visceral Vibratory Vestibular Disturbance

### 4.4.1 Hypothesis

In addition to case reports of symptoms reported by people who live near wind turbines, Pierpont has proposed a hypothesis that purports to explain how some of these symptoms arise: visceral vibratory vestibular disturbance (VVVD) (Pierpont, 2009, pre-publication draft). VVVD has been described as consisting of vibration associated with low frequencies that enters the body and causes a myriad of symptoms. Pierpont considers VVVD to be the most distinctive feature of a nonspecific set of symptoms that she describes as “wind turbine syndrome.” As the name VVVD implies, wind turbine sound in the 4 to 8 Hz spectral region is hypothesized to cause vibrations in abdominal viscera (e.g., intestines, liver, and kidneys) that in turn send neural signals to the part of the brain that normally receives information from the vestibular labyrinth. These signals hypothetically conflict with signals from the vestibular labyrinth and other sensory inputs (visual, proprioceptive), leading to unpleasant symptoms, including panic. Unpleasant symptoms (especially nausea) can certainly be caused by sensory conflict; this is how scientists explain motion sickness. However, this hypothesis of VVVD is implausible based on knowledge of sensory systems and the energy needed to stimulate them. Whether implausible or not, there are time-tested scientific methods available to evaluate the legitimacy of any hypothesis and at this stage, VVVD as proposed by Pierpont is an untested hypothesis. A case series of 10 families recruited to participate in a study based on certain symptoms would not be considered evidence of causality by research or policy institutions such as the International Agency for Research on

Cancer (IARC) or EPA. As noted earlier in this report, a case series of self-selected patients does not constitute evidence of a causal connection.

#### 4.4.2 Critique

Receptors capable of sensing vibration are located predominantly in the skin and joints. A clinical neurological examination normally includes assessment of vibration sensitivity. It is highly unlikely, however, that airborne sound at comfortable levels could stimulate these receptors, because most of airborne sound energy is reflected away from the body.

Takahashi et al. (2005) used airborne sound to produce chest or abdominal vibration that exceeded ambient body levels. This vibration may or may not have been detectable by the subjects. Takahashi found that levels of 100 dB sound pressure level were required at 20 to 50 Hz (even higher levels would have been required at lower and higher frequencies). Sounds like this would be considered by most people to be very loud, and are well beyond the levels produced by wind turbines at residential distances. Comparison of the responses to low frequency airborne sound by normal hearing and profoundly deaf persons has shown that deaf subjects can detect sound transmitted through their body only when it is well above the normal hearing threshold (Yamada et al., 1983). For example, at 16 Hz, the deaf persons' average threshold was 128 dB sound pressure level, 40 dB higher than that of the hearing subjects. It has also been shown that, at higher frequencies, the body surface is very reflective of sound (Katz, 2000). Similarly, work on transmission of low frequency sound into the bodies of sheep has shown a loss of about 30 dB (Peters et al., 1993)

The visceral receptors invoked as a mechanism for VVVD have been shown to respond to static gravitational position changes, but not to vibration (that is why they are called graviceptors). If there were vibration-sensitive receptors in the abdominal viscera, they would be constantly barraged by low frequency body sounds such as pulsatile blood flow and bowel sounds, while external sounds would be attenuated by both the impedance mismatch and dissipation of energy in the overlying tissues. Finally, wind turbine sound at realistic distances possesses little, if any, acoustic energy, at 4 to 8 Hz.

It has been hypothesized that the vestibular labyrinth may be "abnormally stimulated" by wind turbine sound (Pierpont, 2009, pre-publication draft). As noted in earlier sections of this report, moderately loud airborne sound, at frequencies up to about 500 Hz, can indeed stimulate not only the cochlea (the hearing organ) but also the otolith organs. This is not abnormal, and there is no evidence in the medical literature that it is in any way unpleasant or harmful. In ordinary life, most of us are exposed for hours every day to sounds louder than those experienced at realistic distances from wind turbines, with no adverse effects. This assertion that the vestibular labyrinth is stimulated at levels below hearing threshold is based on a misunderstanding of research that used bone-conducted vibration rather than airborne sound. Indeed, those who wear bone conduction hearing aids experience constant stimulation of their vestibular systems, in addition to the cochlea, without adverse effects.

### 4.5 Interpreting Studies and Reports

In light of the unproven hypotheses that have been introduced as reflective of adverse health effects attributed to wind turbines, it can be instructive to review the type of research studies that can be used to determine definitive links between exposure to an environmental



hazard (in this case, sound and vibration emissions from wind turbines) and adverse health effects (the so-called “wind turbine syndrome”).

How do we know, for example, that cigarettes cause lung cancer and that excessive noise causes hearing loss? Almost always, the first indication that an exposure might be harmful comes from the informal observations of doctors who notice a possible correlation between an exposure and a disease, then communicate their findings to colleagues in case reports, or reports of groups of cases (*case series*). These initial observations are usually uncontrolled; that is, there is no comparison of the people who have both exposure and disease to control groups of people who are either non-exposed or disease-free. There is usually no way to be sure that the apparent association is statistically significant (as opposed to simple coincidence), or that there is a causal relationship between the exposure and the disease in question, without control subjects. For these reasons, case reports and case series cannot prove that an exposure is really harmful, but can only help to develop hypotheses that can then be tested in controlled studies (Levine et al., 1994; Genovese, 2004; McLaughlin, 2003).

Once suspicion of harm has been raised, controlled studies (case-control or cohort) are essential to determine whether or not a causal association is likely, and only after multiple independent-controlled studies show consistent results is the association likely to be broadly accepted (IARC, 2006).

*Case-control* studies compare people with the disease to people without the disease (ensuring as far as possible that the two groups are well-matched with respect to all other variables that might affect the chance of having the disease, such as age, sex, and other exposures known to cause the disease). If the disease group is found to be much more likely to have had the exposure in question, and if multiple types of error and bias can be excluded (Genovese, 2004), a causal link is likely. Multiple case-control studies were necessary before the link between smoking and lung cancer could be proved.

*Cohort* studies compare people with the exposure to well-matched control subjects who have not had that exposure. If the exposed group proves to be much more likely to have the disease, assuming error and bias can be excluded, a causal link is likely. After multiple cohort studies, it was clear that excessive noise exposure caused hearing loss (McCunney and Meyer, 2007).

In the case of wind turbine noise and its hypothetical relationships to “wind turbine syndrome” and vibroacoustic disease, the weakest type of evidence – case series – is available, from only a single investigator. These reports can do no more than suggest hypotheses for further research. Nevertheless, if additional and independent investigators begin to report adverse health effects in people exposed to wind turbine noise, in excess of those found in unexposed groups, and if some consistent syndrome or set of symptoms emerges, this advice could change. Thus, at this time, “wind turbine syndrome” and VVVD are unproven hypotheses (essentially unproven ideas) that have not been confirmed by appropriate research studies, most notably cohort and case control studies. However, the weakness of the basic hypotheses makes such studies unlikely to proceed.

## 4.6 Standards for Siting Wind Turbines

### 4.6.1 Introduction

While the use of large industrial-scale wind turbines is well established in Europe, the development of comparable wind energy facilities in North America is a more recent occurrence. The growth of wind and other renewable energy sources is expected to continue. Opponents of wind energy development argue that the height and setback regulations established in some jurisdictions are too lenient and that the noise limits which are applied to other sources of noise (either industrial or transportation) are not sufficient for wind turbines for a variety of reasons. Therefore, they are concerned that the health and well-being of some residents who live in the vicinity (or close proximity) of these facilities is threatened. Critics maintain that wind turbine noise may present more than an annoyance to nearby residents especially at night when ambient levels may be low. Consequently, there are those who advocate for a revision of the existing regulations for noise and setback pertaining to the siting of wind installations (Kamperman and James, 2009). Some have indicated their belief that setbacks of more than 1 mile may be necessary. While the primary purpose of this study was to evaluate the potential for adverse health effects rather than develop public policy, the panel does not find that setbacks of 1 mile are warranted.

### 4.6.2 Noise Regulations and Ordinances

In 1974, EPA published a report that examined the levels of environmental noise necessary to protect public health and welfare (EPA, 1974). Based on the analysis of available scientific data, EPA specified a range of day-night sound levels necessary to protect the public health and welfare from the effects of environmental noise, with a reasonable margin of safety. Rather than establishing standards or regulations, however, EPA simply identified noise levels below which the general public would not be placed at risk from any of the identified effects of noise. Each federal agency has developed its own noise criteria for sources for which they have jurisdiction (i.e., the Federal Aviation Administration regulates aircraft and airport noise, the Federal Highway Administration regulates highway noise, and the Federal Energy Regulatory Commission regulates interstate pipelines (Bastasch, 2005). State and local governments were provided guidance by EPA on how to develop their own noise regulations, but the establishment of appropriate limits was left to local authorities to determine given each community's differing values and land use priorities (EPA, 1975).

### 4.6.3 Wind Turbine Siting Guidelines

Establishing appropriate noise limits and setback distances for wind turbines has been a concern of many who are interested in wind energy. There are several approaches to regulating noise, from any source, including wind turbines. They can generally be classified as absolute or relative standards or a combination of absolute and relative standards. Absolute standards establish a fixed limit irrespective of existing noise levels. For wind turbines, a single absolute limit may be established regardless of wind speed (i.e., 50 dBA) or different limits may be established for various wind speeds (i.e., 40 dBA at 5 meters per second [m/s] and 45 dBA at 8 m/s). The Ontario Ministry of Environment (2008) wind turbine noise guidelines is an example of fixed limits for each integer wind speed between 4 and 10 meters per second. Relative standards limit the increase over existing levels and may

also establish either an absolute floor or ceiling beyond which the relative increase is not considered. That is, for example, if a relative increase of 10 dBA with a ceiling of 50 dBA is allowed and the existing level is 45 dBA, a level of 55 dBA would not be allowed. Similarly, if a floor of 40 dBA was established and the existing level is 25 dBA, 40 dBA rather than 35 dBA would be allowed. Fixed distance setbacks have also been discussed. Critics of this approach suggest that fixed setbacks do not take into account the number or size of the turbines nor do they consider other potential sources of noise within the project area. It is clear that like many other sources of noise, a uniform regulator approach for wind turbine noise has not been established either domestically or internationally.

A draft report titled *Environmental Noise and Health in the UK*, published for comment in 2009 by the Health Protection Agency (HPA) on behalf of an ad hoc expert group, provides insightful comments on the World Health Organization's noise guidelines (WHO, 1999). The HPA draft report can be viewed at the following address:

[http://www.hpa.org.uk/web/HPAwebFile/HPAweb\\_C/1246433634856](http://www.hpa.org.uk/web/HPAwebFile/HPAweb_C/1246433634856)

The HPA report states the following:

*It is important to bear in mind that the WHO guideline values, like other WHO guidelines, are offered to policymakers as a contribution to policy development. They are not intended as standards in a formal sense but as a possible basis for the development of standards. By way of overall summary, the 1998 NPL report noted [a British report titled Health-Based Noise Assessment Methods – A Review and Feasibility Study (Porter et al., 1998) as quoted in HPA 2009]:*

*The WHO guidelines represent a consensus view of international expert opinion on the lowest noise levels below which the occurrence rates of particular effects can be assumed to be negligible. Exceedances of the WHO guideline values do not necessarily imply significant noise impact and indeed, it may be that significant impacts do not occur until much higher degrees of noise exposure are reached. The guidelines form a starting point for policy development. However, it will clearly be important to consider the costs and benefits of reducing noise levels and, as in other areas, this should inform the setting of objectives.*

*(From: HPA, 2009, p. 77)*

The HPA report further states the following:

*Surveys have shown that about half of the UK population lives in areas where daytime sound levels exceed those recommended in the WHO Community Noise Guidelines. About two-thirds of the population live in areas where the night-time guidelines recommended by WHO are exceeded. (p. 81)*

*That sleep can be affected by noise is common knowledge. Defining a dose-response curve that describes the relationship between exposure to noise and sleep disturbance has, however, proved surprisingly difficult. Laboratory studies and field studies have generated different results. In part this is due to habituation to noise which, in the field, is common in many people. (p. 82)*

*Our examination of the evidence relating to the effects of environmental noise on health has demonstrated that this is a rapidly developing area. Any single report will, therefore, need to be revised within a few years. We conclude and recommend that an*

*independent expert committee to address these issues on a long-term basis be established. (p. 82)*

The statements cited above from the HPA and WHO documents address general environmental noise concerns rather than concerns focused solely on wind turbine noise.

# Conclusions

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Many countries have turned to wind energy as a key strategy to generate power in an environmentally clean manner. Wind energy enjoys considerable public support, but it has its detractors, who have publicized their concerns that the sounds emitted from wind turbines cause adverse health consequences.

The objective of the panel was to develop an authoritative reference document for the use of legislators, regulators, and citizens simply wanting to make sense of the conflicting information about wind turbine sound. To this end, the panel undertook extensive review, analysis, and discussion of the peer-reviewed literature on wind turbine sound and possible health effects. The varied professional backgrounds of panel members (audiology, acoustics, otolaryngology, occupational and environmental medicine, and public health) were highly advantageous in creating a diversity of informed perspectives. Participants were able to examine issues surrounding health effects and discuss plausible biological effects with considerable combined expertise.

Following review, analysis, and discussion, the panel reached agreement on three key points:

- There is nothing unique about the sounds and vibrations emitted by wind turbines.
- The body of accumulated knowledge about sound and health is substantial.
- The body of accumulated knowledge provides no evidence that the audible or subaudible sounds emitted by wind turbines have any direct adverse physiological effects.

The panel appreciated the complexities involved in the varied human reactions to sound, particularly sounds that modulate in intensity or frequency. Most complaints about wind turbine sound relate to the aerodynamic sound component (the swish sound) produced by the turbine blades. The sound levels are similar to the ambient noise levels in urban environments. A small minority of those exposed report annoyance and stress associated with noise perception.

This report summarizes a number of physical and psychological variables that may influence adverse reactions. In particular, the panel considered “wind turbine syndrome” and vibroacoustic disease, which have been claimed as causes of adverse health effects. The evidence indicates that “wind turbine syndrome” is based on misinterpretation of physiologic data and that the features of the so-called syndrome are merely a subset of annoyance reactions. The evidence for vibroacoustic disease (tissue inflammation and fibrosis associated with sound exposure) is extremely dubious at levels of sound associated with wind turbines.

The panel also considered the quality of epidemiologic evidence required to prove harm. In epidemiology, initial case reports and uncontrolled observations of disease associations

need to be confirmed through controlled studies with case-control or cohort methodology before they can be accepted as reflective of casual connections between wind turbine sound and health effects. In the area of wind turbine health effects, no case-control or cohort studies have been conducted as of this date. Accordingly, allegations of adverse health effects from wind turbines are as yet unproven. Panel members agree that the number and uncontrolled nature of existing case reports of adverse health effects alleged to be associated with wind turbines are insufficient to advocate for funding further studies.

In conclusion:

1. Sound from wind turbines does not pose a risk of hearing loss or any other adverse health effect in humans.
2. Subaudible, low frequency sound and infrasound from wind turbines do not present a risk to human health.
3. Some people may be annoyed at the presence of sound from wind turbines. Annoyance is not a pathological entity.
4. A major cause of concern about wind turbine sound is its fluctuating nature. Some may find this sound annoying, a reaction that depends primarily on personal characteristics as opposed to the intensity of the sound level.

## SECTION 6

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APPENDIX A

# Fundamentals of Sound

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# Fundamentals of Sound

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The following appendix provides additional background information on sound and how it is defined.

One atmospheric pressure is given by 100,000 pascals (Pa), where one pascal is one Newton per square meter ( $\text{N}/\text{m}^2$ ), and a sound pressure of 94 dB re  $20\mu\text{Pa}$  is given by 1 Pa (See later for decibels). The frequency of the fluctuations may be between 20 times a second (20 Hz), and up to 20,000 times a second (20,000 Hz) for the “audible” noise. Frequencies below 20 Hz are commonly called “infrasound,” although there is a very fuzzy boundary between infrasound and low frequency noise. Infrasound at high levels is audible. Low frequency noise might be from about 10 Hz to about 200 Hz.

In addition to frequency, the quantities which define a sound wave include:

- Pressure, P
- Wavelength,  $\lambda$
- Velocity,  $c = 340\text{m}/\text{s}$  approx, depending on temperature

The velocity and wavelength are related by: velocity = wavelength  $\times$  frequency,

Relating frequency and wavelength by velocity gives

Freq Hz	16	31.5	63	125	250	500	1000	2000	4000
Wavelength m	21	11	5.4	2.7	1.4	0.68	0.34	0.17	0.085

Low frequencies have long wavelengths. It is useful to develop an appreciation of frequencies and related wavelengths, since this helps an understanding of noise propagation and control.

Sound pressure in a wave is force per unit of area of the wave and has units of  $\text{N}/\text{m}^2$ , which is abbreviated to Pa. The sound pressure fluctuates above and below atmospheric pressure by a very small amount.

The sound power is a characteristic of the source, and is its rate of production of energy, expressed in watts. The sound power is the fundamental property of the source, whilst the sound pressure at a measurement location depends on the transmission path from source to receiver. Most sound sources, including wind turbines, are specified in terms of their sound power. The sound power of a wind turbine is typically in the 100-105 dBA range, which is similar to that of a leaf blower. The sound power is used to predict propagation of the sound, where the source is assumed to be at the hub.

## Sound Levels

The decibel is the logarithm of the ratio between two values of a quantity such as power, pressure or intensity, with a multiplying constant to give convenient numerical factors. Logarithms are useful for compressing a wide range of quantities into a smaller range. For example:

$$\begin{aligned}\log_{10}10 &= 1 \\ \log_{10}100 &= 2 \\ \log_{10}1000 &= 3\end{aligned}$$

The ratio of 1000:10 is compressed into a ratio of 3:1.

This approach is advantageous for handling sound levels, where the ratio of the highest to the lowest sound which we are likely to encounter is as high as 1,000,000 to 1. A useful development, many years ago, was to take the ratios with respect to the quietest sound which we can hear. This is the threshold of hearing at 1,000 Hz, which is 20 microPascals ( $\mu\text{Pa}$ ) ( $2 \times 10^{-5} \text{Pa}$ ) of pressure for the average young healthy person. Sound powers in decibels are taken with respect to a reference level of  $10^{-12}$  watts.

When the word “level” is added to the word for a physical quantity, decibel levels are implied, denoted by  $L_x$ , where  $x$  is the symbol for the quantity.

$$\text{Pressure level } L_p = 20 \log_{10} \left[ \frac{P}{P_0} \right] \text{ dB}$$

where  $P$  is the measured pressure and  $P_0$  is the reference pressure level of  $2 \times 10^{-5} \text{ Pa}$

A little calculation allows us to express the sound pressure level at a distance from a source of known sound power level as

$$\text{Sound pressure level, } L_P = L_w - 20 \log[r] - 11 \text{ dB}$$

Where  $L_p$  is the sound pressure level  
 $L_w$  is the sound power level of the source  
 $r$  is the distance from the source

This is the basic equation for spherical sound propagation. It is used in prediction of wind turbine sound but, in a real calculation, has many additions to it, to take into account the atmospheric, ground and topographic conditions. However, as a simple calculation, the sound level at a distance of 500m from a source of sound power 100 dBA is 35 dBA.

Equivalent level ( $L_{eq}$ ): This is a steady level over a period of time, which has the same energy as that of the fluctuating level actually occurring during that time. A-weighted equivalent level, designated  $L_{Aeq}$ , is used for many legislative purposes, including for assessment of wind turbine sound.

Percentiles (LN)L These are a statistical measure of the fluctuations in overall noise level, that is, in the envelope of the noise, which is usually sampled a number of times per second, typically ten times. The most used percentiles are  $L_{90}$  and  $L_{10}$ . The  $L_{90}$  is the level exceeded for 90 percent of the time and represents a low level in the noise. It is often used to assess

background noise. The L10 is the level exceeded for 10 percent of the time and is a measure of the higher levels in a noise. Modern computing sound level meters give a range of percentiles. Note that the percentile is a statistical measure over a specified time interval.

## Frequency Analysis

This gives more detail of the frequency components of a noise. Frequency analysis normally uses one of three approaches: octave band, one-third octave band or narrow band.

Narrow band analysis is most useful for complex tonal noises. It could be used, for example, to determine a fan tone frequency, to find the frequencies of vibration transmission from machinery or to detect system resonances. All analyses require an averaging over time, so that the detail of fluctuations in the noise is normally lost.

Criteria for assessment of noise are based on dBA, octave bands, or 1/3-octave band measurements. These measures clearly give increasingly detailed information about the noise.

APPENDIX B

# The Human Ear

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# The Human Ear

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Humans have ears with three general regions:

1. An *outer ear*, including an ear (auditory) canal
2. An air-containing *middle ear* that includes an eardrum and small bones called ossicles (three in mammals, one in other animals)
3. An *inner ear* that includes organs of hearing (in mammals, this is the organ of Corti in the cochlea) and balance (vestibular labyrinth)

Airborne sound passes thorough the ear canal, making the eardrum and ossicles vibrate, and this vibration then sets the fluids of the cochlea into motion. Specialized “hair cells” convert this fluid movement into nerve impulses that travel to the brain along the auditory nerve. The hair cells, nerve cells, and other cells in the cochlea can be damaged by excessive noise, trauma, toxins, ear diseases, and as part of the aging process. Damage to the cochlea causes “sensorineural hearing loss,” the most common type of hearing loss in the United States.

It is essential to understand the role of the middle ear, as well as the difference between air conduction and bone conduction. The middle ear performs the essential task of converting airborne sound into inner ear fluid movement, a process known as impedance matching (air is a low-impedance medium, meaning that its molecules move easily in response to sound pressure, while water is a high-impedance medium). Without impedance matching, over 99.9 percent of airborne sound energy is reflected away from the body. The middle ear enables animals living in air to hear very soft sounds that would otherwise be inaudible, but it is unnecessary for animals that live in water, because sound traveling in water passes easily into the body (which is mostly water). When a child has an ear infection, or an adult places earplugs in his ears, a “conductive hearing loss” dramatically reduces the transmission of airborne sound into the inner ear. People with conductive hearing loss can still hear sounds presented directly to the skull by “bone conduction.” This is how both humans and fishes hear underwater or when a vibrating tuning fork is applied to the head, but it requires much more acoustic energy than air conduction hearing.

APPENDIX C  
**Measuring Sound**

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# Measuring Sound

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A sound level meter is the standard way of measuring sound. Environmental sound is normally assessed by the A-weighting. Although hand-held instruments appear to be easy to use, lack of understanding of their operation and limitations, and the meaning of the varied measurements which they can give, may result in misleading readings.

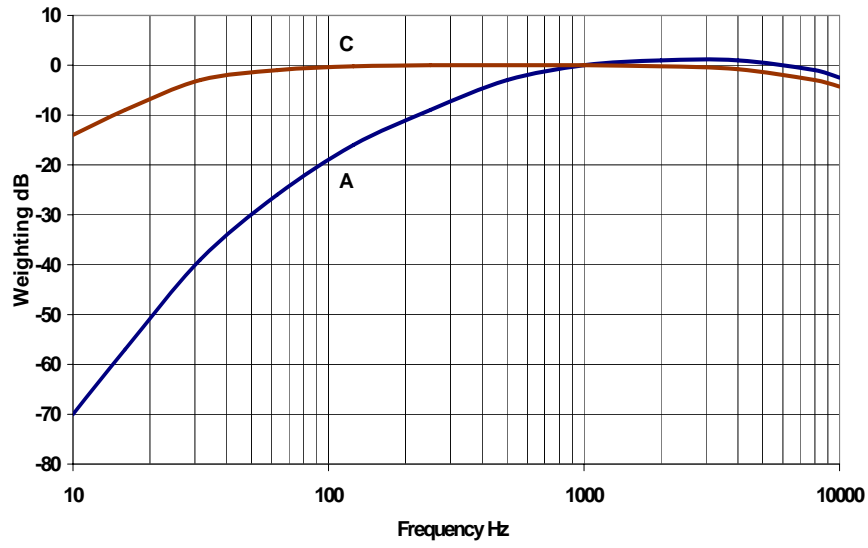
The weighting network and electrical filters are an important part of the sound level meter, as they give an indication of the frequency components of the sound. The filters are as follows:

- A-weighting: on all meters
- C-weighting: on most meters
- Linear (Z-weighting): on many meters
- Octave filters: on some meters
- Third octave filters: on some meters
- Narrow band: on a few meters

Sound level meter weighting networks are shown in Figure C-1. Originally, the A-weighting was intended for low levels of noise. C-weighting was intended for higher levels of noise. The weighting networks were based on human hearing contours at low and high levels and it was hoped that their use would mimic the response of the ear. This concept, which did not work out in practice, has now been abandoned and A- and C-weighting are used at all levels. Linear weighting is used to detect low frequencies. A specialist G-weighting is used for infrasound below 20 Hz.

Figure C-1 shows that the A-weighting depresses the levels of the low frequencies, as the ear is less sensitive to these. There is general consensus that A-weighting is appropriate for estimation of the hazard of NIHL. With respect to other effects, such as annoyance, A-weighting is acceptable if there is largely middle and high frequency noise present, but if the noise is unusually high at low frequencies, or contains prominent low frequency tones, the A-weighting may not give a valid measure. Compared with other noise sources, wind turbine spectra, as heard indoors at typical separation distances, have less low frequency content than most other sources (Pedersen, 2008).

FIGURE C-1  
Weighting Networks





APPENDIX D

# Propagation of Sound

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# Propagation of Sound

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The propagation of noise from wind turbines is determined by a number of factors, including:

- Geometrical spreading, given by  $K = 20\log[r] - 11$  dB, at a distance  $r$
- Molecular absorption. This is conversion of acoustic energy to heat and is frequency dependent
- Turbulent scattering from local variations in wind velocity and air temperature and is moderately frequency dependent
- Ground effects – reflection, topography and absorption are frequency dependent; their effects increasing as the frequency increases
- Near surface effects – temperature and wind gradients.

The sound pressure at a point, distant from source, is given by

$$L_P = L_W - K - D - A_A - A_G \quad (\text{dB})$$

In which:

$L_P$  is the sound pressure at the receiving point

$L_W$  is the sound power of the turbine in decibels re  $10^{-12}$  watts

$K$  is the geometrical spreading term, which is inherent in all sources

$D$  is a directivity index, which takes non-uniform spreading into account

$A_A$  is an atmospheric absorption and other near surface effects term

$A_G$  is a ground absorption and other surface effects term

Near surface meteorological effects are complex, as wind and temperature gradients affect propagation through the air.

APPENDIX E

# Expert Panel Members

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# Expert Panel Members

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Members of the expert panel are listed below. Biographies of each member are provided following the list.

## Expert Panel Members

**W. David Colby, M.D.**

Chatham-Kent Medical Officer of Health (Acting)  
Associate Professor, Schulich School of Medicine & Dentistry, University of Western Ontario

**Robert Dobie, M.D.**

Clinical Professor, University of Texas, San Antonio  
Clinical Professor, University of California, Davis

**Geoff Leventhall, Ph.D.**

Consultant in Noise Vibration and Acoustics, UK

**David M. Lipscomb, Ph.D.**

President, Correct Service, Inc.

**Robert J. McCunney, M.D.**

Research Scientist, Massachusetts Institute of Technology Department of Biological Engineering,  
Staff Physician, Massachusetts General Hospital Pulmonary Division; Harvard Medical School

**Michael T. Seilo, Ph.D.**

Professor of Audiology, Western Washington University

**Bo Søndergaard, M.Sc. (Physics)**

Senior Consultant, Danish Electronics Light and Acoustics (DELTA)

## Technical Advisor

**Mark Bastasch**

Acoustical Engineer, CH2M HILL

## Panel Member Biographies

### W. David Colby, M.D.

W. David Colby M.Sc., M.D., FRCPC, is a fellow of the Royal College of Physicians and Surgeons of Canada in Medical Microbiology. Dr Colby is the Acting Medical Officer of Health in Chatham-Kent, Ontario and Associate Professor of Medicine, Microbiology/Immunology and Physiology/Pharmacology at the Schulich School of Medicine and Dentistry at the University of Western Ontario. He received his M.D. from the University of Toronto and completed his residency at University Hospital, London, Ontario. While still a resident he was given a faculty appointment and later was appointed Chief of Microbiology and Consultant in Infectious Diseases at University Hospital. Dr Colby lectures extensively on antimicrobial chemotherapy, resistance and fungal infections in addition to a busy clinical practice in Travel Medicine and is a Coroner for the province of Ontario. He has received numerous awards for his teaching. Dr. Colby has a number of articles in peer-reviewed journals and is the author of the textbook *Optimizing Antimicrobial Therapy: A Pharmacometric Approach*. He is a Past President of the Canadian Association of Medical Microbiologists. On the basis of his expertise in Public Health, Dr Colby was asked by his municipality to assess the health impacts of wind turbines. The report, titled *The Health Impact of Wind Turbines: A Review of the Current White, Grey, and Published Literature* is widely cited internationally.

### Robert Dobie, M.D.

Robert Dobie, M.D., is clinical professor of otolaryngology at both the University of Texas Health Science Center at San Antonio and the University of California-Davis. He is also a partner in Dobie Associates, a consulting practice specializing in hearing and balance, hearing conservation, and ear disorders. The author of over 175 publications, his research interests include age-related and noise-induced hearing loss, as well as tinnitus and other inner ear disorders. He is past president of the Association for Research in Otolaryngology, past chair of the Hearing and Equilibrium Committee of the American Academy of Otolaryngology-Head and Neck Surgery, and has served on the boards and councils of many other professional organizations and scholarly journals.

### Geoff Leventhall, Ph.D.

Geoff is a UK-based noise and vibration consultant who works internationally. His academic and professional qualifications include Ph.D. in Acoustics, Fellow of the UK Institute of Physics, Honorary Fellow of the UK institute of Acoustics (of which he is a former President), Distinguished International Member of the USA Institute of Noise Control Engineering, Member of the Acoustical Society of America.

He was formerly an academic, during which time he supervised 30 research students to completion of their doctoral studies in acoustics. Much of his academic and consultancy work has been on problems of infrasound and low frequency noise and control of low frequency noise by active attenuation

He has been a member of a number of National and International committees on noise and acoustics and was recently a member of two committees producing reports on effects of noise on health: the UK Health Protection Agency Committee on the Health Effects of

Ultrasound and Infrasound and the UK Department of Health Committee on the Effects of Environmental Noise on Health.

**David M. Lipscomb, Ph.D.**

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Dr. Seilo has consulted with industries on the prevention of NIHL and he has collaborated with other professionals in the assessment of hearing-loss related claims pertaining to noise.

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## Technical Advisor Biography

**Mark Bastasch**

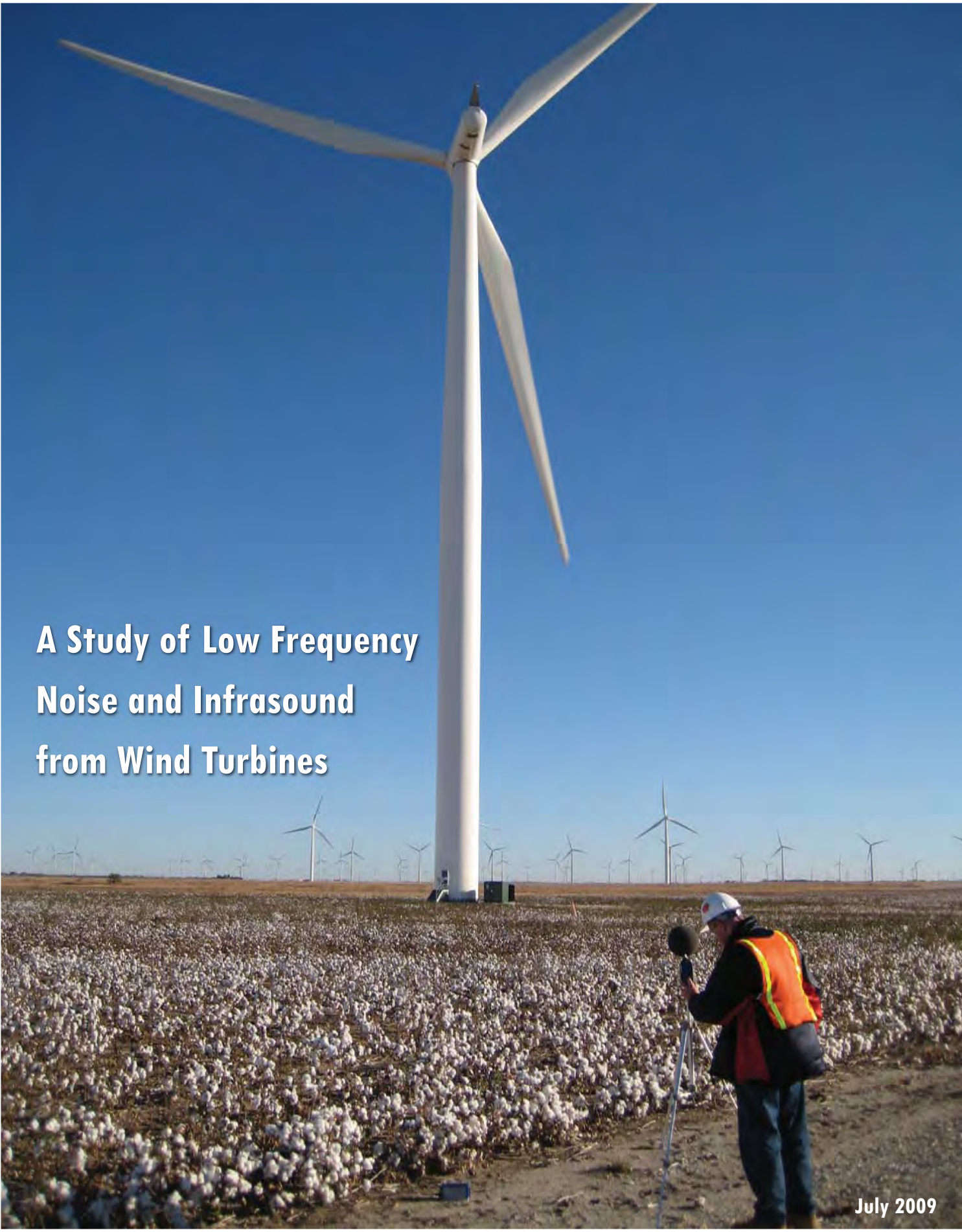
Mr. Bastasch is a registered acoustical engineer with CH2M HILL. Mr. Bastasch assisted AWEA and CanWEA in the establishment of the panel and provided technical assistance to the panel throughout the review process. Mr. Bastasch's acoustical experience includes preliminary siting studies, regulatory development and assessments, ambient noise measurements, industrial measurements for model development and compliance purposes, mitigation analysis, and modeling of industrial and transportation noise. His wind turbine experience includes some of the first major wind developments including the Stateline project, which when built in 2001 was the largest in the world. He also serves on the organizing committee of the biannual International Wind Turbine Noise Conference, first held in Berlin, Germany, in 2005.

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We acknowledge the following person for suggestions and comments on the manuscript. The final responsibility for the content remains with the authors.

**Richard K. Jennings, M.D. —Psychiatrist, Retired**





## A Study of Low Frequency Noise and Infrasound from Wind Turbines

July 2009

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## ES EXECUTIVE SUMMARY

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Early down-wind wind turbines in the US created low frequency noise; however current up-wind wind turbines generate considerably less low frequency noise. The results of Epsilon Associates, Inc. (Epsilon) analysis and field testing indicate that there is no audible infrasound either outside or inside homes at the any of the measurement sites – the closest site was approximately 900 feet from a wind farm. Wind farms at distances beyond 1000 feet meet the ANSI standard for low frequency noise in bedrooms, classrooms, and hospitals, meet the ANSI standard for thresholds of annoyance from low frequency noise, and there should be no window rattles or perceptible vibration of light-weight walls or ceilings within homes. In homes there may be slightly audible low frequency noise (depending on other sources of low frequency noise); however, the levels are below criteria and recommendations for low frequency noise within homes. In accordance with the above findings and in conjunction with our extensive literature search of scientific papers and reports, there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 1000 feet from the wind turbine types measured by Epsilon: GE 1.5sle and Siemens SWT 2.3-93.

**Siemens SWT 2.3-93 Wind Turbine.** Outdoor measurements of Siemens SWT 2.3-93 wind turbines under high output and relatively low ground wind speed (which minimized effects of wind noise) at 1000 feet indicate that infrasound is inaudible to the most sensitive people (more than 20 dB lower than median thresholds of hearing); that outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met; that the low frequency sounds are compatible with ANSI S12.9 Part 4 levels for minimal annoyance and beginning of rattles; that levels meet outdoor equivalent UK Department for Environment, Food and Rural Affairs (DEFRA) disturbance-based guidelines for use by Environmental Health Officers, and that low frequency sounds might be audible in some cases. Based on the comparisons made to these criteria, there are no low frequency noise problems from Siemens SWT 2.3-93 wind turbines at 1000 feet or beyond.

Indoor measurements of two homes with windows open and closed of Siemens SWT 2.3-93 wind turbines at approximately 920 feet (under high output, maximum noise, and high ground winds) and at 1060 feet (under moderate-high output, maximum noise and relatively low ground winds) indicate infrasound is inaudible to the most sensitive people (more than 25 dB lower than median thresholds of hearing). The low frequency noise at 50 Hz and above might be slightly audible depending on background noises within the home or other external noises. The ANSI/ASA S12.2 low frequency criteria for bedrooms, classrooms and hospitals were met, as were the criteria for moderately perceptible vibrations in light-weight walls and ceilings. DEFRA disturbance based guidelines were met for steady low frequency sounds and were within 2 dB for non-steady low frequency sounds. Based on the comparisons made to these criteria, there are no low frequency noise problems indoors from Siemens SWT 2.3-93 wind turbines at 920 feet or beyond.

**GE 1.5sle Wind Turbine.** Outdoor measurements of GE 1.5sle wind turbines under high output and relatively low ground wind speed (which minimized effects of wind noise) at 1000 feet indicate that infrasound is inaudible to the most sensitive people (more than 20 dB lower than median thresholds of hearing); that outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are

met; that the low frequency sounds are compatible with ANSI S12.9 Part 4 levels for minimal annoyance and beginning of rattles; that levels meet or are within 1 dB of outdoor equivalent DEFRA disturbance-based guidelines; and that the low frequency sounds might be audible in some cases. Based on the comparisons made to these criteria, there are no low frequency noise problems from GE 1.5sle wind turbines at 1000 feet or beyond.

Indoor measurements with windows open and closed of GE 1.5sle wind turbines at approximately 950 feet (under moderate output, maximum noise, and high ground winds) and at approximately 1025 feet (under moderate output, within 1.5 dBA of maximum noise, and high ground winds) indicate infrasound is inaudible to the most sensitive people (more than 25 dB lower than median thresholds of hearing). The low frequency noise at or above 50 or 63 Hz might be slightly audible depending on background noises within the home or other external noises. The ANSI/ASA S12.2 low frequency criteria for bedrooms, classrooms and hospitals were met, as were the criteria for moderately perceptible vibrations in light-weight walls and ceilings. DEFRA disturbance based guidelines were met for steady low frequency sounds and non-steady low frequency sounds. Based on the comparisons made to these criteria, there are no low frequency noise problems indoors for GE 1.5sle wind turbines at distances beyond 950 feet.

**Conclusions.** Siemens SWT 2.93-93 and GE 1.5sle wind turbines at maximum noise at a distance more than 1000 feet from the nearest residence do not pose a low frequency noise problem. At this distance the wind farms:

- ◆ meet ANSI/ASA S12.2 indoor levels for low frequency sound for bedrooms, classrooms and hospitals;
- ◆ meet ANSI/ASA S12.2 indoor levels for moderately perceptible vibrations in light-weight walls and ceilings;
- ◆ meet ANSI S12.9 Part 4 thresholds for annoyance and beginning of rattles;
- ◆ meet UK DEFRA disturbance based guidelines;
- ◆ have no audible infrasound to the most sensitive listeners;
- ◆ might have slightly audible low frequency noise at frequencies at 50 Hz and above depending on other sources of low frequency noises in homes, such as refrigerators or external traffic or airplanes; and
- ◆ meet ANSI S2.71 recommendations for perceptible ground-borne vibration in residences during night time hours.

## 1.0 INTRODUCTION

---

Epsilon Associates, Inc. (“Epsilon”) has been retained by NextEra Energy Resources, LLC (“NextEra”), formerly FPL Energy, to investigate whether the operation of their wind turbines may create unacceptable levels of low frequency noise and infrasound. This question has been posed to NextEra, and other wind energy developers and operators of utility-scale wind turbines. NextEra is one of the world’s largest generators of wind power with approximately 6,400 net megawatts (MW) as of April 2009.

Epsilon determined all means, methods, and the testing protocol without interference or direction from NextEra. No limitations were placed on Epsilon by NextEra with respect to the testing protocol or upon the analysis methods.

This report is composed of two distinct sections: the first portion defines terms, discusses known effects of low frequency sound, and presents scientific guidelines and standards used to evaluate low frequency sound. The second portion of the report examines specific wind turbines used by NextEra, including data from field measurements at operating wind farms, and compares the measured data to guidelines and standards. In addition, each NextEra wind turbine vendor supplied detailed, reference sound level data in both A-weighted and octave band format in accordance with the international standard IEC 61400-11, “Wind Turbine Generator Systems-Part 11; Acoustic Noise Measurement Techniques.” These data were used as an aide to focus the field portion of the measurement program.

## 2.0 DEFINITIONS

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### 2.1 Low Frequency Noise/Sound

The frequency range 20 – 20,000 Hz is commonly described as the range of “audible” noise. The frequency range of low frequency sound is generally from 20 Hertz (Hz) to 200 Hz, and the range below 20 Hz is often described as “infrasound”. However, audibility extends to frequencies below 20 Hz.

Low frequency sound has several definitions. American National Standards ANSI/ASA S12.2 and ANSI S12.9 Part 4 have provisions for evaluating low frequency noise, and these special treatments apply only to sounds in the octave bands with 16, 31.5, and 63-Hz mid-band frequencies. For these reasons, in this paper on wind turbine noise, we use the term “low frequency noise” to include 12.5 Hz – 200 Hz with emphasis on the 16 Hz, 31Hz and 63 Hz octave bands with a frequency range of 11 Hz to 89 Hz.

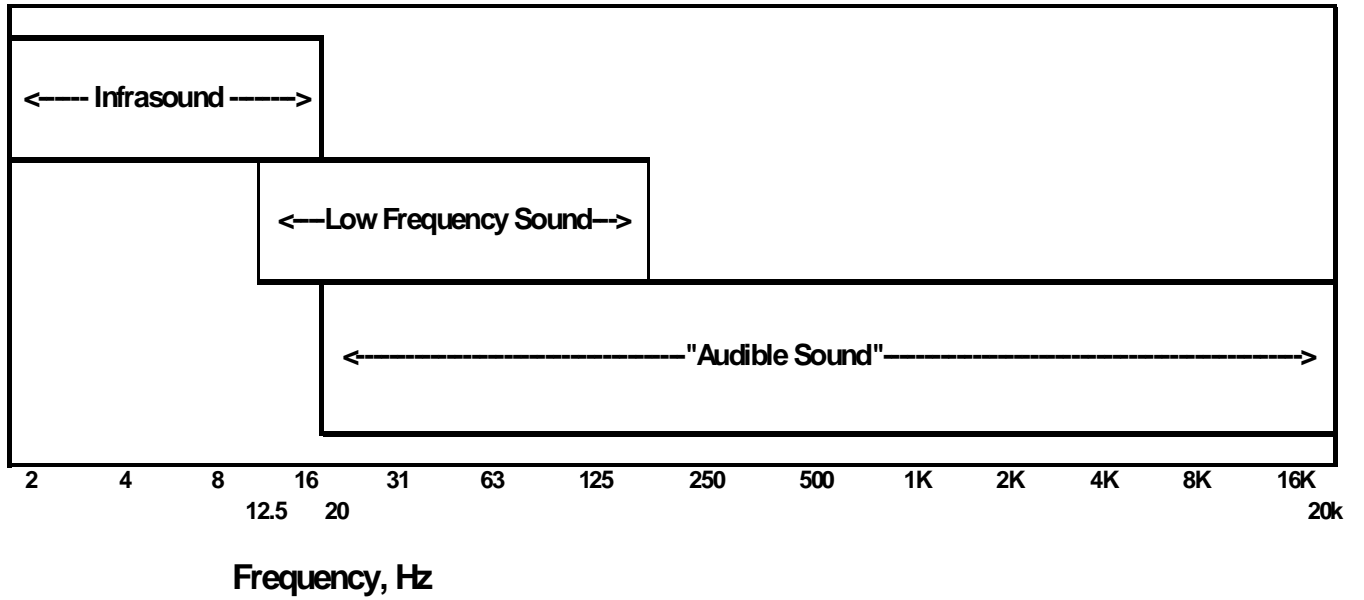
### 2.2 Infrasound

IEC 60050-801:1994 “International Electrotechnical Vocabulary – Chapter 801: Acoustics and electroacoustics” defines “*infrasound*” as “Acoustic oscillations whose frequency is below the low frequency limit of audible sound (about 16 Hz).” This definition is *incorrect* since sound remains audible at frequencies well below 16 Hz provided that the sound level is sufficiently high. In this paper we define infrasound to be below 20 Hz, which is the limit for the standardized threshold of hearing.

Figure 2.2-1 shows these frequency regions and their common labels. Since there is no sharp change in hearing at 20 Hz, the division into “low-frequency sound” and “infrasound” should only be considered “practical and conventional.”



Figure 2.2-1 Frequency Range of "Infrasound", "Low Frequency Sound", and "Audible Sound".



## 3.0 EFFECTS OF LOW FREQUENCY SOUND AND INFRASOUND

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### 3.1 Humans

#### 3.1.1 *Threshold of hearing*

Moeller and Pedersen (2004) present an excellent summary on human perception of sound at frequencies below 200 Hz. The ear is the primary organ for sensing infrasound. Hearing becomes gradually less sensitive for decreasing frequencies. But, humans with a normal hearing organ can perceive infrasound at least down to a few hertz if the sound level is sufficiently high.

The threshold of hearing is standardized for frequencies down to 20 Hz (ISO 226:2003). Based on extensive research and data, Moeller and Pedersen propose normal hearing thresholds for frequencies below 20 Hz (see Figure 3.1-1). Moeller and Pedersen suggest that the curve for normal hearing is “probably correct within a few decibels, at least in most of the frequency range.”

The hearing thresholds show considerable variability from individual to individual with a standard deviation among subjects of about 5 dB independent of frequency between 3 Hz and 1000 Hz with a slight increase at 20 – 50 Hz. This implies that the audibility threshold for 97.5% of the population is greater than the values in Figure 3.1-1 minus 10 dB and for 84% of the population is greater than the values in Figure 3.1-1 minus 5 dB. Moeller and Pedersen suggest using the pure-tone thresholds in Figure 3.1-1 for non-sinusoidal sound; this relationship is what is used in ISO 226 (International Organization for Standardization) for frequencies down to 20 Hz.

Below 20 Hz as frequency decreases, if the noise source is tonal, the tonal sensation ceases. Below 20 Hz tones are perceived as discontinuous. Below 10 Hz it is possible to perceive the single cycles of a tone, and the perception changes into a sensation of pressure at the ears.

#### 3.1.2 *Loudness*

Below 100 Hz, the dynamic range of the auditory system decreases with decreasing frequency, and the compressed dynamic range has an effect on equal loudness contours: a slight change in sound level can change the perceived loudness from barely audible to loud. This combined with the large variation in individual hearing may mean that a low frequency sound that is inaudible to some may be audible to others, and may be relatively loud to some of those for whom it is audible. Loudness for low frequency sounds grows considerably faster above threshold than for sounds at higher frequencies. (Moeller and Pedersen, 2004)

### **3.1.3        *Non-auditory perceptions***

Non-auditory perception of low frequency and infrasound occurs only at levels above the auditory threshold. In the frequency range of 4 – 25 Hz and at “*levels 20 - 25 dB above [auditory] threshold it is possible to feel vibrations* in various parts of the body, e.g., the lumbar, buttock, thigh and calf regions. A feeling of pressure may occur in the upper part of the chest and the throat region” [emphasis added]. (Moeller and Pedersen, 2004).

## **3.2        Residential Structures**

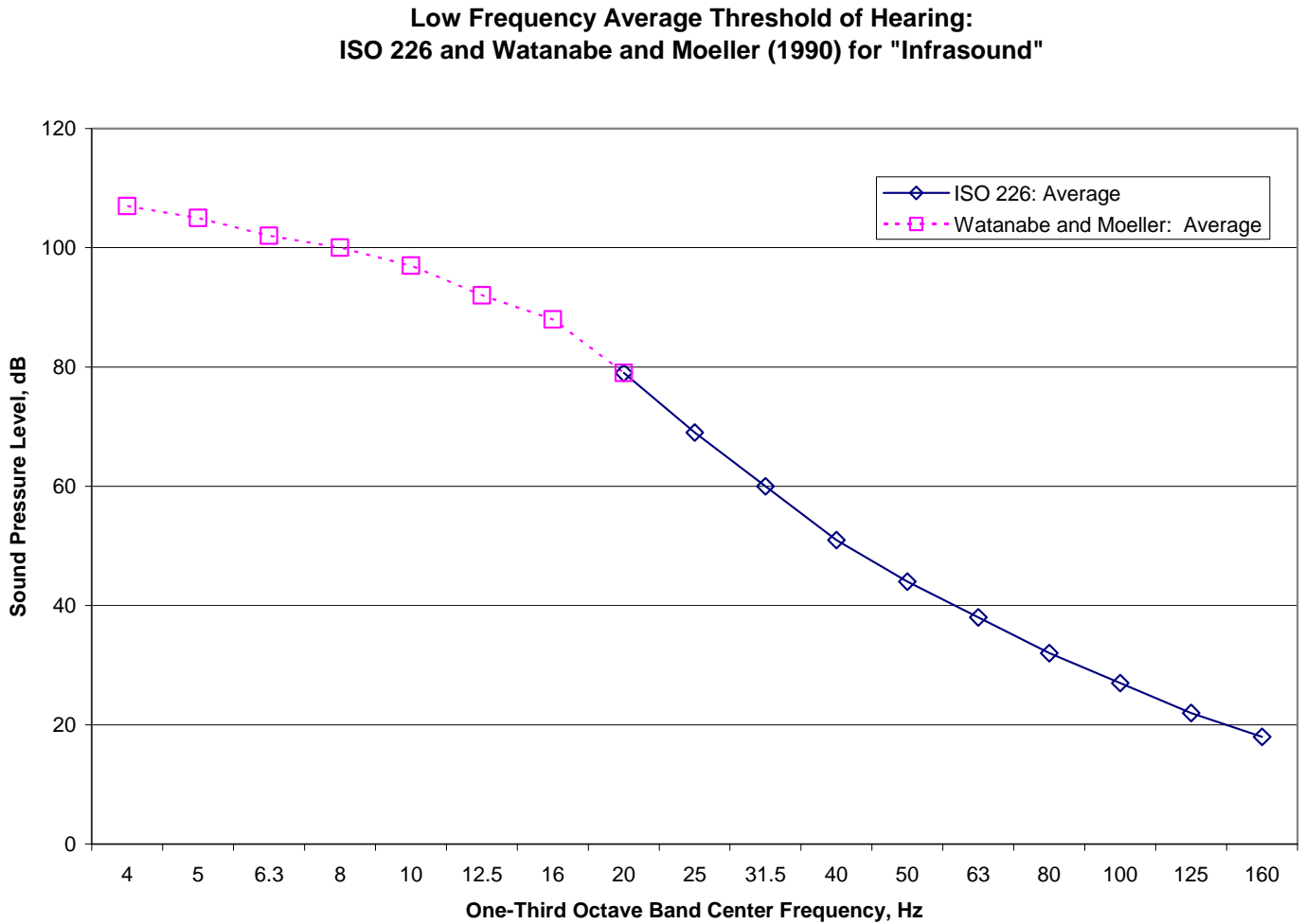
### **3.2.1        *Airborne Vibration***

Outdoor low frequency sounds of sufficient amplitude can cause building walls to vibrate and windows to rattle. Homes have low values of transmission loss at low frequencies, and low frequency noise of sufficient amplitude may be audible within homes. Window rattles are not low frequency noise, but may be caused by low frequency noise.

### **3.2.2        *Ground borne Vibration***

While not studied nearly as extensively as noise, a few papers were found that examined ground borne vibration from wind turbines (Styles, P. et al, 2005; Hayes McKenzie Partnership, 2006; Gastmeier and Howe (2008)). Measurement of ground borne vibration associated with wind turbine operations were detectable with instruments but were below the threshold of perception, even within the wind farm (Gastmeier and Howe 2008; Snow, D.J., 1997).

Figure 3.1-1 Low Frequency Average Threshold of Hearing



## 4.0 GUIDELINES AND CRITERIA

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### 4.1 United States Government

There are no specific criteria for low frequency noise in the United States. The US Environmental Protection Agency (EPA) has guidelines for the protection of public health with an adequate margin of safety in terms of annual average A-weighted day-night average sound level ( $L_{dn}$ ), but there are no corrections or adjustments for low frequency noise. The US Department of Transportation (DOT) has A-weighted sound pressure level criteria for highway projects and airports, but these do not have adjustments for low frequency noise.

### 4.2 American National Standards (voluntary)

#### 4.2.1 *ANSI/ASA S12.9-2007/Part 5*

ANSI/ASA S12.9-2007/Part 5 “Quantities and Procedures for description and measurement of environmental sound. Part 5: Sound Level Descriptors for Determination of Compatible Land Use” has an informative annex which provides guidance for designation of land uses compatible with existing or predicted sound levels. The noise metric in ANSI S12.9 Part 5 is the annual average of the adjusted day-night average outdoor sound level (DNL). Ranges of the DNL are outlined, within which a specific region of compatibility may be drawn. These ranges take into consideration the transmission loss in sound level from outside to inside buildings as commonly constructed in that locality and living habits there. There are adjustments to day-night average sound level to account for the presence of low frequency noise, and the adjustments are described in ANSI S12.9 Part 4.

#### 4.2.2 *ANSI S12.9-2005/Part 4*

ANSI S12.9-2005 Part 4 “Quantities and Procedures for description and measurement of environmental sound. Part 4: Noise assessment and prediction of long-term community response” provides procedures for assessing outdoor environmental sounds and provides for *adjustments* to measured or predicted adjusted annual outdoor day-night A-weighted sound level to account “for the change in annoyance caused by ... sounds with strong low-frequency content...”

ANSI S12.9 Part 4 does not specifically define the frequency range for “low-frequency” sounds; however, evaluation methods for low frequency noise in Annex D use a sum of the sound pressure levels in the 16, 31 and 63 Hz octave bands. Procedures apply only when the difference in exterior C-weighted and A-weighted sound levels is greater than 10 dB, ( $L_{pC} - L_{pA}$ ) > 10 dB. Complicated procedures are given for adjustments to  $L_{Aeq}$  and  $L_{dn}$  values. Adjustments are significant for high levels of low frequency sound.

ANSI S12.9 Part 4 states: “Generally, annoyance is minimal when octave-band sound pressure levels are less than 65 dB at 16, 31.5, and 63-Hz mid-band frequencies. However, low-frequency sound characterized by rapidly fluctuating amplitude ... may cause annoyance when these octave-band sound pressure levels are less than 65 dB.”

For sounds with strong low-frequency content, adjusted sound exposure level (LNE) is calculated from low-frequency sound pressure level  $L_{LF}$  by:

$$\begin{aligned} LNE &= 2(L_{LF} - 65) + 55 + 10\log(t/1) \\ &= 2 L_{LF} - 75 + 10\log(t/1) \end{aligned} \quad \text{(Equation D.1 of ANSI S12.9 Part 4)}$$

where  $L_{LF}$  is 10 times the logarithm of the ratio of time-mean square sound pressures in the 16, 31.5, and 63-Hz octave bands divided by the square of the reference sound pressure and

$t$  is the time duration of interest, in seconds, over which the low-frequency sound is present.

The factor of 2 in equation (D.1) accounts for the rapid increase in annoyance with sound pressure level at low frequencies. ANSI S12.9 Part 4 states: “Equation (D.1) also accounts for the additional annoyance from rattles that begins when the low-frequency sound pressure level [ $L_{LF}$ ] exceeds 75 dB.” Later, ANSI S12.9/Part 4 has a contradictory recommendation: “To prevent the likelihood of noise-induced rattles, the low-frequency sound pressure level [ $L_{LF}$ ] should be less than 70 dB.”

ANSI S12.9 /Part 4 identifies two thresholds: annoyance is minimal when the 16, 31.5 and 63 Hz octave band sound pressure levels are each less than 65 dB and there are no rapidly fluctuations of the low frequency sounds. The second threshold is for increased annoyance which begins when rattles occur, which begins at  $L_{LF}$  70 - 75 dB. Since determination of  $L_{LF}$  involves integrating concurrently the sound pressures in the three octave bands, an energy sum of the levels in each of these separate bands results in an upper bound to  $L_{LF}$ . (The sound pressure level from the summation of these bands will always be less than  $L_{LF}$  since the sound pressures are not in phase within these three bands.)

It should be noted that a recent study on low frequency noise from aircraft operations (Hodgdon, Atchley, Bernhard 2007) reported that an expert panel was critical of using this  $L_{LF}$  metric because it had not previously been used to characterize aircraft noise and its reliance on the 16 Hz band since aircraft data does not extend down to 16 Hz and can not be used with the FAA Integrated Noise Model.

The adjustment procedure for low frequency noise to the average annual A-weighted sound pressure level in ANSI S12.9 Part 4 uses a different and more complicated metric and procedure (Equation D.1) than those used for evaluating low frequency noise in rooms contained in ANSI/ASA S12.2. (See section 4.2.3). Since we are evaluating low frequency

noise and not A-weighted levels, we do not recommend using the procedure for adjusting A-weighted levels. Instead we recommend using the following two guidelines from ANSI S12.4 Part 9: a sound pressure level of 65 dB in each of the 16-, 31.5-, and 63 Hz octave bands as an indicator of minimal annoyance, and 70 - 75 dB for the summation of the sound pressure levels from these three bands as an indicator of possible increased annoyance from rattles. This method is conservative since the sum of the levels in the three bands will always be less than  $L_{LF}$ .

#### 4.2.3 ANSI/ASA S12.2-2008

ANSI/ASA S12.2-2008 discusses criteria for evaluating room noise, and has two separate provisions for evaluating low frequency noise: (1) the potential to cause perceptible vibration and rattles, and (2) meeting low frequency portions of room criteria curves.

Vibration and Rattles: Clause 6 and Table 6 of this standard contain limiting values of sound pressure levels for vibrations and rattles from low frequency noise. The frequency range is not defined, but limiting values and discussion relate only to octave-bands with center frequencies of 16, 31 and 63 Hz. This is the same narrow frequency range from low-frequency sounds as in ANSI S12.9/Part 4. Therefore, ANSI S12.9 Part 4 and ANSI/ASA S12.2 are consistent in evaluating and assessing low frequency sounds both for annoyance (interior and exterior measurements) and vibration (interior measurements) by using sound pressure levels only in the 16, 31 and 63 Hz octave-bands.

ANSI/ASA S12.2 presents limiting levels at low frequencies for assessing (a) the probability of *clearly* perceptible acoustically induced vibration and rattles in lightweight wall and ceiling constructions, and (b) the probability of *moderately* perceptible acoustically induced vibration in similar constructions. These 16, 31.5 and 63 Hz octave band sound pressure level values are presented in Table 4.2-1. One set of values is for when “clearly perceptible vibration and rattles” is likely, and a lower set of values is for when “moderately perceptible vibration and rattles” is likely.

**Table 4.2-1 Measured interior sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures. [ANSI/ASA S12.2-2008]**

Condition	Octave-band center frequency (Hz)		
	16	31.5	63
Clearly perceptible vibration and rattles likely	75 dB	75 dB	80 dB
Moderately perceptible vibration and rattles likely	65 dB	65 dB	70 dB

Since indoor measurements are not always possible, for comparison to outdoor sound levels the indoor criteria from ANSI/ASA S12.2 should be adjusted. Outdoor to indoor low frequency noise reductions have been reported by Sutherland for aircraft and highway noise

for open and closed windows (Sutherland 1978) and by Hubbard for aircraft and wind turbine noise for closed windows (Hubbard 1991). Table 4.2-2 presents the average low frequency octave band noise reductions from outdoor to indoors from these two papers for open and closed windows. Sutherland only reported values down to 63 Hz; whereas Hubbard presented values to less than 10 Hz. The closed window conditions of Hubbard were used to estimate noise reductions less than 63 Hz by applying the difference between values for open and closed windows from Sutherland data at 63 Hz. It should be noted that the attenuation for wind turbines in Hubbard is based on only three homes at two different wind farms, whereas the traffic and aircraft data are for many homes. The wind turbine open window values were obtained from the wind turbine closed window values by subtracting the difference in values between windows closed and open obtained by Sutherland.

**Table 4.2-2 Average low frequency octave band noise reductions from outdoor to indoors in dB (based on Sutherland (1978) and Hubbard (1991))**

Noise Source	Window condition	Octave Band Center Frequency		
		16 Hz	31.5 Hz	63 Hz
Average aircraft and traffic sources	Closed windows	16	15	18
Average aircraft and traffic sources	Open Windows	(11)*	(10)*	12
Average Wind Turbine	Closed Windows	8	11	14
<b>Average Wind Turbine</b>	<b>Open Windows</b>	<b>(3)**</b>	<b>(6)* +</b>	<b>9+</b>

\* No data are available for windows open below 63 Hz octave band. The values for 16 Hz and 31 Hz were obtained by subtracting the difference between the levels for 63 Hz closed and open conditions to the 16 and 31 Hz closed values.

+ Used in this report to determine equivalent outdoor criteria from indoor criteria

To be conservative, we use the open window case instead of closed windows. To be further conservative, we use the wind turbine data (adjusted to open windows), which is based on only three homes. However, it should be noted that it is possible for some homes to have some slight amplification at low frequencies with windows open due to possible room resonances. Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table 4.2-2 to the ANSI/ASA S12.2 indoor sound pressure levels in Table 4.2-1 yields the *equivalent* outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 4.2-3.



**Table 4.2-3** *Equivalent* outdoor sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures based on Tables 4.2-1 and 4.2-2 above for wind turbines.

Condition	Octave-band center frequency (Hz)		
	16	31.5	63
Clearly perceptible vibration and rattles likely	78 dB	81 dB	89 dB
Moderately perceptible vibration and rattles likely	68 dB	71 dB	79 dB

Room Criteria Curves: ANSI/ASA S12.2 has three primary methods for evaluating the suitability of noise within rooms: a survey method - A-weighted sound levels, an engineering method – noise criteria (NC) curves and a method for evaluating low-frequency fluctuating noise using room noise criteria (RNC) curves. “The RNC method should be used to determine noise ratings when the noise from HVAC systems at low frequencies is *loud* and is suspected of containing *sizeable fluctuations or surging.*” [emphasis added] The NC curves are appropriate to evaluate low frequency noise from wind turbines in homes since wind turbine noise does not have significant fluctuating low frequency noise sufficient to warrant using RNC curves and since A-weighted sound levels do not adequately determine if there are low frequency problems. [ANSI/ASA S12.2. section 5.3 gives procedures for determining if there are large fluctuations of low frequency noise.]

Annex C.2 of this standard contains recommendations for bedrooms, which are the most stringent rooms in homes: NC and RNC criteria curve between 25 and 30. The recommended NC and RNC criteria for schools and private rooms in hospitals are the same. The values of the sound pressure levels in the 16 – 250 Hz octave bands for NC curves 25 and 30 are shown in Table 4.2-4.

**Table 4.2-4** Octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [From Table 1 of ANSI/ASA S12.2]

	Octave-band-center frequency in Hz				
	16	31.5	63	125	250
NC-25	80	65	54	44	37
NC-30	81	68	57	48	41

ANSI/ASA S12.2 also presents a method to determine if the levels below 500 Hz octave band are too high in relation to the levels in the mid-frequencies which could create a condition of “spectrum imbalance”. The method for this evaluation is:

- ◆ Calculate the speech interference level (SIL) for the measured spectrum. [SIL is the arithmetic average of the sound pressure levels in the 500, 1000, 2000 and 4000 Hz octave bands.] Select the NC curve equal to the SIL value.
- ◆ Plot the measured spectra and the NC curve equal to the SIL value on the same graph and determine the differences between the two curves in the octave bands below 500 Hz.
- ◆ Estimate the likelihood that the excess low-frequency levels will annoy occupants of the space using Table 4.2-5.

**Table 4.2-5 Measured sound pressure level deviations from an NC (SIL) curve that may lead to serious complaints [From ANSI/ASA S12.2:2008].**

Octave-band frequency, Hz = >	Measured Spectrum – NC(SIL), dB			
	31.5	63	125	250
Possible serious dissatisfaction	*	6 - 9	6 - 9	6 - 9
Likely serious dissatisfaction	*	>9	>9	>9

\*Insufficient data available to evaluate

### 4.3 Other Criteria

#### 4.3.1 *World Health Organization (WHO)*

No specific low frequency noise criteria are proposed by the WHO. The Guidelines for Community Noise report (WHO, 1999) mentions that if the difference between dBC and dBA is greater than 10 decibels, then a frequency analysis should be performed to determine if there is a low frequency issue. A document prepared for the World Health Organization states that “there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for ‘normal’ sounds. Reactions caused by extremely intense levels of infrasound can resemble those of mild stress reaction and may include bizarre auditory sensations, describable as pulsation and flutter” [Berglund (1995) p. 41]

#### 4.3.2 *The UK Department for Environment, Food, and Rural Affairs (DEFRA)*

The report prepared by the University of Salford for the UK Department for Environment, Food, and Rural Affairs (DEFRA) on low frequency noise proposed one-third octave band sound pressure level  $L_{eq}$  criteria and procedures for assessing low frequency noise [DEFRA (2005)]. The guidelines are based on complaints of disturbance from low frequency sounds and are intended to be used by Environmental Health Officers. Reports by Hayes (2006) and others refer to the proposed criteria as “DEFRA criteria.” Tables 4.3-1 and 4.3-2 present

the DEFRA criteria for assessment of low frequency noise measured indoors. The criteria are “based on 5 dB below the ISO 226 (2003) average threshold of audibility for steady [low frequency] sounds.” However, the DEFRA criteria are at 5 dB lower than ISO 226 only at 20 - 31.5 Hz; at higher frequencies the criteria are equal to the Swedish criteria which are higher levels than ISO 226 less 5 dB. For frequencies lower than 20 Hz, DEFRA uses the thresholds from Watanabe and Moeller (1990) less 5 dB. In developing the DEFRA guidelines, The University of Salford reviewed and considered existing low frequency noise criteria from several European countries.

The DEFRA criteria are based on measurements in an unoccupied room. Hayes Mackenzie (2006) noted that measurements should be made with windows closed; however, we conservatively used windows open conditions for our assessment. If the low frequency sound is “steady” then the criteria may be relaxed by 5 dB. A low frequency noise is considered steady if either of the conditions a) or b) below is met in the third octave band which exceeds the criteria by the greatest margin:

a)  $L_{10}-L_{90} < 5\text{dB}$

b) the rate of change of sound pressure level (Fast time weighting) is less than 10 dB per second

Applying indoor to outdoor one-third octave band transfer functions for open windows (from analysis in Sutherland (1978) and Hubbard (1991) yields *equivalent* one-third octave band sound pressure level proposed DEFRA criteria for outdoor sound levels. Table 4.3-1 presents both the indoor DEFRA proposed criteria and equivalent proposed criteria for outdoors for non-steady low-frequency sounds. Table 4.3-2 presents the DEFRA proposed criteria for a steady low frequency sound.

**Table 4.3-1 DEFRA proposed criteria for the assessment of low frequency noise disturbance: *indoor* and *equivalent outdoor*  $L_{eq}$  one-third sound pressure levels for *non-steady* low frequency sounds. [DEFRA (2005)]**

Location	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Indoor $L_{eq}$ , dB	92	87	83	74	64	56	49	43	42	40	38	36	34
<i>Equivalent</i> Outdoor $L_{eq}$ , dB	94	89	86	78	68.5	61	56	51	51	49	47	45	43

**Table 4.3-2** DEFRA criteria for the assessment of low frequency noise disturbance: *indoor and equivalent outdoor*  $L_{eq}$  one-third sound pressure levels for *steady* low frequency sounds. [DEFRA (2005)]

Location	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Indoor $L_{eq}$ , dB	97	92	88	79	69	61	54	48	47	45	43	41	39
Equivalent Outdoor* $L_{eq}$ , dB	99	94	91	83	73.5	66	61	56	56	54	52	50	48

\* With windows open

#### 4.3.3 *C-weighted minus A-weighted ( $L_{pC} - L_{pA}$ )*

Leventhall (2003) and others indicate that the difference in C-weighted and A-weighted sound pressure levels can be a predictor of annoyance. Leventhall states that if  $(L_{pC} - L_{pA})$  is greater than 20 dB there is “a potential for a low frequency noise problem.” He further states that  $(L_{pC} - L_{pA})$  cannot be a predictor of annoyance but is a simple indicator that further analysis may be needed. This is due in part to the fact that the low frequency noise may be inaudible even if  $(L_{pC} - L_{pA})$  is greater than 20 dB.

#### 4.3.4 *Threshold of hearing*

ISO 226:2003 gives one-third octave band threshold of hearing down to 20 Hz. Watanabe and Moeller (1990) have extended these to 10 Hz and lower, and the values are reported in Moeller and Pedersen (2004). Denmark has established low frequency noise criteria based on audibility. The Danish criteria are “based on hearing thresholds for the 10% most sensitive people in an ontologically unselected population aged 50-60 years. These 10% thresholds are typically about 4-5 dB lower than the average threshold for ontologically normal young adults (18-25 years) as given in ISO 226.” [DEFRA (2005)]. Other reports indicate that the standard deviation of these thresholds is also about 5 dB. Table 4.3-3 presents one-third octave band threshold of hearing according to ISO 226 and Watanabe and Moeller. The second row in Table 4.3-3 presents the values that are 5 dB less than the threshold.

**Table 4.3-3** Threshold of audibility from ISO 226 and Watanabe and Moeller (1990)

	One-Third Octave band center frequency, Hz																
	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Threshold	107	105	102	100	97	92	88	79	69	60	51	44	38	32	27	22	18
Threshold - 5 dB	102	100	97	95	92	87	83	74	64	55	46	39	33	27	22	17	13

The average threshold of hearing values in Table 4.3-3 are also shown in Figure 3.1-1.

#### **4.3.5**        *Ground-Borne Vibration*

ANSI S2.71-1983 (formerly ANSI S3.29-1983) presents recommendations for magnitudes of ground-borne vibration which humans will perceive and possibly react to within buildings. A basic rating is given for the most stringent conditions, which correspond to the approximate threshold of perception of the most sensitive humans. From the base rating, multiplication factors should be applied according to the location of the receiver; for continuous sources of vibration in residences at nighttime, the multiplication factor is 1.0 – 1.4.

ANSI S2.71-1983 presents one-third octave band acceleration or velocity ratings for z-axis, and x-, y-axis vibrations. For spaces in which the occupants may be sitting, standing, or lying at various times, the standard recommends using a combined axis rating which is obtained from the most stringent rating for each axis. Measurements in each of the 3 axes should be compared to the combined axis rating. Table 4.3-4 presents the base response velocity ratings for the combined axis. The velocity ratings are for root-mean-square (RMS) values.

**Table 4.3-4 Base response one-third octave band RMS velocity ratings for the three biodynamic vibration axes and combined axis (From ANSI S2.71-1983 (R2006))**

One-Third Octave band center frequency, Hz	Velocity (RMS), m/s		
	z axis	x, y axis	Combined axis
1	$1.6 \times 10^{-3}$	$5.7 \times 10^{-4}$	$5.7 \times 10^{-4}$
1.25	$1.1 \times 10^{-3}$	$4.6 \times 10^{-4}$	$4.6 \times 10^{-4}$
1.6	$8.0 \times 10^{-4}$	$3.6 \times 10^{-4}$	$3.6 \times 10^{-4}$
2	$5.6 \times 10^{-4}$	$2.9 \times 10^{-4}$	$2.9 \times 10^{-4}$
2.5	$4.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$2.4 \times 10^{-4}$
3.15	$2.9 \times 10^{-4}$	$2.9 \times 10^{-4}$	$2.1 \times 10^{-4}$
4	$2.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.7 \times 10^{-4}$
5	$1.6 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.4 \times 10^{-4}$
6.3	$1.3 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.2 \times 10^{-4}$
8	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
10	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
12.5	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
16	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
20	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
25	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
31.5	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
40	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
50	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
63	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$
80	$1.0 \times 10^{-4}$	$2.9 \times 10^{-4}$	$1.0 \times 10^{-4}$

## 5.0 LITERATURE REVIEW

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Epsilon performed an extensive literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound - hearing, effects, measurement, and criteria. The following paragraphs briefly summarize the findings from some of these papers and reports.

### 5.1 H. Moeller and C. S. Pedersen (2004)

Moeller and Pedersen (2004) present a comprehensive summary on hearing and non-auditory perception of sound at low and infrasonic regions, some of which has been cited in sections 3.1.1, 3.1.2, and 3.1.3 of this report.

### 5.2 Leventhall (2003)

Leventhall presents an excellent study on low frequency noise from all sources and its effects. The report presents criteria in place at that time. Included are figures and data relating cause and effects.

### 5.3 Leventhall (2006)

Leventhall reviewed data and allegations on alleged problems from low frequency noise and infrasound from wind turbines. Leventhall concluded the following: "It has been shown that there is insignificant infrasound from wind turbines and that there is normally little low frequency noise." "Turbulent air inflow conditions cause enhanced levels of low frequency noise, which may be disturbing, but the overriding noise from wind turbines is the fluctuating audible swish, mistakenly referred to as "infrasound" or "low frequency noise". "Infrasound from wind turbines is below the audible threshold and of no consequence". Other studies have shown that wind turbine generated infrasound levels are below threshold of perception and threshold of feeling and body reaction.

### 5.4 Delta (2008)

The Danish Energy Authority project on "low frequency noise from large wind turbines" comprises a series of investigations in the effort to give increased knowledge on low frequency noise from wind turbines. One of the conclusions of the study is that wind turbines do not emit audible infrasound, with levels that are "far below the hearing threshold." Audible low frequency sound may occur both indoors and outdoors, "but the levels in general are close to the hearing and/or masking level." "In general the noise in the critical band up to 100 Hz is below both thresholds". The summary report notes that for road traffic noise (in the vicinity of roads) the low frequency noise levels are higher [than wind turbine] both indoors and outdoors.

## 5.5 Hayes McKenzie (2006)

Hayes McKenzie performed a study for the UK Department of Trade & Industry (DTI) to investigate complaints of low frequency noise that came from three of the five farms with complaints out of 126 wind farms in the UK. The study concluded that:

- ◆ Infrasound associated with modern wind turbines is not a source which will result in noise levels that are audible or which may be injurious to the health of a wind farm neighbor.
- ◆ Low frequency noise was measureable on a few occasions, but below DEFRA criteria. Wind turbine noise may result in indoor noise levels within a home that is just above the threshold of audibility; however, it was lower than that of local road traffic noise.
- ◆ The common cause of the complaints was not associated with low frequency noise but the occasional audible modulation of aerodynamic noise, especially at night. Data collected indoors showed that the higher frequency modulated noise levels were insufficient to awaken the residents at the three sights; however, once awake, this noise could result in difficulties in returning to sleep.

The UK Department of Trade and Industry, which is now the UK Department for Business Enterprise and Regulatory Reform (BERR), summarized the Hayes McKenzie report: “The report concluded that there is no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines.” [BERR (2007)]

## 5.6 Howe (2006)

Howe performed extensive studies on wind turbines and infrasound and concluded that infrasound was not an issue for modern wind turbine installations – “while infrasound can be generated by wind turbines, it is concluded that infrasound is not of concern to the health of residences located nearby.” Since then Gastmeier and Howe (2008) investigated an additional situation involving the alleged “perception of infrasound by individual.” In this additional case, the measured indoor infrasound was at least 30 dB below the perception threshold given by Watanabe and Moeller (1990) as presented in Table 4.3-3. Gastmeier and Howe (2008) also performed vibration measurements at the residence and nearest wind turbine, and concluded that the vibration levels were well below the perception limits discussed in ISO 2631-2.



## 5.7 Branco (2004)

Branco and other Portuguese researchers have studied possible physiological affects associated with high amplitude low frequency noise and have labeled these alleged effects as “Vibroacoustic Disease” (VAD). “Vibroacoustic disease (VAD) is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to low frequency noise.” Hayes (2007, 2008) concluded that levels from wind farms are not likely to cause VAD after comparing noise levels from alleged VAD cases to noise levels from wind turbines in homes of complainers. Noise levels in aircraft in which VAD has been hypothesized are considerably higher than wind turbine noise levels. Hayes also concluded that it is “unlikely that symptoms will result through induced internal vibration from incident wind farm noise.” [Hayes (2007)] Other studies have found no VAD indicators in environmental sound that have been alleged by VAD proponents. [ERG (2001)]

## 5.8 French National Academy of Medicine (2006)

French National Academy of Medicine recommended “*as a precaution* construction should be suspended for wind turbines with a capacity exceeding 2.5 MW located within 1500 m of homes.” [emphasis added] However, this precaution is not because of definitive health issues but because:

- ◆ sound levels one km from some wind turbine installations “occasionally exceed allowable limits” for France (note that the allowable limits are long term averages)
- ◆ French prediction tools for assessment did not take into account sound levels created with wind speeds greater than 5 m/s.
- ◆ Wind turbine noise has been compared to aircraft noise (even though the sound levels of wind turbine noise are significantly lower), and exposure to high level aircraft noise “involves neurobiological reactions associated with an increased frequency of hypertension and cardiovascular illness. Unfortunately, no such study has been done near wind turbines.” [Gueniot (2006)].

In March 2008, the French Agency for Environmental and Occupational Health Safety (AFSSET) published a report on “the health impacts of noise generated by wind turbines”, commissioned by the Ministries of Health and Environment in June 2006 following the report of the French National Academy of Medicine in March 2006. [AFSSET (2008)] The AFSSET study recommends that one does not define a fixed distance between wind farms and homes, but rather to model the acoustic impact of the project on a case-by-case basis. One of the conclusions of the AFSSET report is: “The analysis of available data shows: The absence of identified direct health consequences concerning the auditory effects or specific effects usually associated with exposure to low frequencies at high level.” (“L'analyse des données disponibles met en évidence: L'absence de conséquences sanitaires directes recensées en ce qui concerne les effets auditifs, ou les effets spécifiques généralement attachés à l'exposition à des basses fréquences à niveau élevé.”)

## 6.0 REPRESENTATIVE WIND TURBINES

At the direction of NextEra, two types of utility-scale wind turbines were studied:

- ◆ General Electric (GE) 1.5sle (1.5 MW), and
- ◆ Siemens SWT-2.3-93 (2.3 MW).

Typical hub height for these wind turbines is 80 meters above ground level (AGL).

Sound levels for these wind turbine generators (WTGs) vary as a function of wind speed from cut-in wind speed to maximum sound level. Table 6.0-1 below lists the reference sound power levels of each WTG as a function of wind speed at 10 meters AGL as provided by the manufacturer. This is in conformance with the sound level standard for wind turbines [IEC 61400-11].

**Table 6.0-1 Sound power levels as a Function of Wind Speed (dBA)**

Wind Speed at 10 meters AGL (m/s)	GE 1.5 sle 80 m hub height; 77 m rotor diameter	Siemens SWT-2.3-93 80 m hub height; 92.4 m rotor diameter
3	< 96	ND
4	< 96	ND
5	99.1	99
6	103.0	103.4
7	≤104	104.9
8	≤104	105.1
9	≤104	105.0
10	≤104	105.0

ND = No Data available

Each wind turbine manufacturer applied the uncertainty factor K of 2 dBA to guarantee the turbine's sound power level. (According to IEC TS 61400-14, K accounts for both measurement variations and production variation.) The results in Section 8.0 use the manufacturer's guaranteed value, that is, 2 dBA above the levels in Table 6.0-1.

One-third octave band sound power level data have also been provided for each turbine reflective of the highest A-weighted level (typically a wind speed of 8 m/s or greater at 10 m AGL). These data are reference (not guaranteed) data, and are summarized below in Table 6.0-2. Cut-in wind speed for the GE 1.5 sle wind turbine is 3.5 m/s while the Siemens wind turbine has a cut-in wind speed of 4 m/s. The last two rows in Table 6.0-2 contain the overall A-weighted sound power levels from Table 6.0-1 and the guaranteed values.

Table 6.0-2 One-Third Octave Sound Power Levels at 8 m/s (un-weighted, dB)

1/3 Octave Band Center Frequency, Hz	GE 1.5 sle 80 m hub height; 77 m rotor diameter	Siemens SWT-2.3-93 80 m hub height; 92.4 m rotor diameter
25	ND	109.0
31.5	ND	105.7
40	ND	105.3
50	106.4	105.3
63	106.1	104.8
80	105.1	104.7
100	103.9	104.8
125	102.8	105.3
160	105.8	103.2
200	101.6	103.7
250	100.6	105.0
315	100.6	102.5
400	99.1	100.2
500	97.0	97.8
630	95.1	95.8
800	94.8	93.5
1000	92.8	92.7
1250	91.7	90.6
1600	90.5	88.2
2000	88.4	87.1
2500	85.8	85.6
3150	83.6	83.9
4000	81.2	82.1
5000	78.1	80.8
6300	76.0	79.9
8000	72.4	79.4
10000	73.3	80.0
<b>Overall - Reference</b>	<b>104 dBA</b>	<b>105 dBA</b>
<b>Guaranteed</b>	<b>106 dBA</b>	<b>107 dBA</b>

ND = No data provided.

## 7.0 FIELD PROGRAM

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Real-world data were collected from operating wind turbines to compare to the low frequency noise guidelines and criteria discussed previously in Section 4.0. These data sets consisted of outdoor measurements at various reference distances, and concurrent indoor/outdoor measurements at residences within the wind farm. Epsilon determined all means, methods, and the testing protocol without interference or direction from NextEra. No limitations were placed on Epsilon by NextEra with respect to the testing protocol or upon the analysis methods.

### 7.1 GE 1.5sle and Siemens SWT-2.3-93

Field measurements were conducted in order to measure sound levels at operating wind turbines, and compare them to the guidelines and criteria discussed in this report. NextEra provided access to the Horse Hollow Wind Farm in Taylor and Nolan Counties, Texas in November 2008 to collect data on the GE 1.5 sle and Siemens SWT-2.3-93 wind turbines. The portion of the wind farm used for testing is relatively flat with no significant terrain. The land around the wind turbines is rural and primarily used for agriculture and cattle grazing. The siting of the sound level measurement locations was chosen to minimize local noise sources except the wind turbines and the wind itself.

Two noise consultants collected sound level and wind speed data over the course of one week under a variety of operational conditions. Weather conditions were dry the entire week with ground level winds ranging from calm to 28 mph (1-minute average). In order to minimize confounding factors, the data collection tried to focus on periods of maximum sound levels from the wind turbines (moderate to high hub height winds) and light to moderate ground level winds.

Ground level (2 meters AGL) wind speed and direction were measured continuously at one representative location. Wind speeds near hub height were also measured continuously using the permanent meteorological towers maintained by the wind farm.

A series of simultaneous interior and exterior sound level measurements were made at four houses owned by participating landowners within the wind farm. Two sets were made of the GE WTGs, and two sets were made of the Siemens WTGs. Data were collected with both windows open and windows closed. Due to the necessity of coordinating with the homeowners in advance, and reasonable restrictions of time of day to enter their homes, the interior/exterior measurement data sets do not always represent ideal conditions. However, enough data were collected to compare to the criteria and draw conclusions on low frequency noise.

Sound level measurements were also made simultaneously at two reference distances from a string of wind turbines under a variety of wind conditions. Using the manufacturer's sound level data discussed in Section 6.0, calculations of the sound pressure levels as a function of distance in flat terrain were made to aid in deciding where to collect data in the field. Based on this analysis, two distances from the nearest wind turbine were selected - 1000 feet and 1500 feet - and were then used where possible during the field program.

Distances much larger than 1,500 feet were not practical since an adjacent turbine string could be closer and affect the measurements, or would put the measurements beyond the boundaries of the wind farm property owners. Brief background sound level measurements were conducted several times during the program whereby the Horse Hollow Wind Farm operators were able to shutdown the nearby WTGs for a brief (20 minutes) period. This was done in real time using cell phone communication.

All the sound level measurements described above were attended by the noise consultants. One series of unattended overnight measurements was made at two locations for approximately 15 hours to capture a larger data set. One measurement was set up approximately 1,000 feet from a GE 1.5 sle WTG and the other was set up approximately 1,000 feet from a Siemens WTG. The location was chosen based on the current wind direction forecast so that the sound level equipment would be downwind for the majority of the monitoring period. By doing this, the program was able to capture periods of strong hub-height winds and moderate to low ground-level winds.

Ground-borne vibration measurements were made within the Horse Hollow Wind Farm. Measurements were made 400 feet and 1000 feet downwind from both GE 1.5 sle and Siemens 2.3 MW WTGs under full operation. In addition, background vibration measurements were made with the WTGs briefly shutdown.

## 7.2 Measurement Equipment

Ground level wind speed and direction were measured with a HOBO H21-002 micro weather station (Onset Computer Corporation). The data were sampled every three seconds and logged every one minute. All sound levels were measured using two Norsonic Model Nor140 precision sound analyzers, equipped with a Norsonic-1209 Type 1 Preamplifier, a Norsonic-1225 half-inch microphone and a 7-inch Aco-Pacific untreated foam windscreens Model WS7. The instrumentation meets the "Type 1 - Precision" requirements set forth in American National Standards Institute (ANSI) S1.4 for acoustical measuring devices. The microphone was tripod-mounted at a height of five feet above ground. The measurements included simultaneous collection of broadband (A-weighted) and one-third-octave band data (0.4 hertz to 20,000 hertz bands). Sound level data were primarily logged in 10-minute intervals to be consistent with the wind farm's Supervisory Control And Data Acquisition (SCADA) system which provides power output (kW) in 10-minute increments. A few sound level measurements were logged using 20-minute intervals. The meters were calibrated and certified as accurate to standards set by the National Institute of Standards and Technology. These calibrations were conducted by an independent laboratory within the past 12 months.

The ground-borne vibration measurements were made using an InstanTel Minimate Plus vibration and overpressure monitor. A triaxial geophone inserted in the ground measured the particle velocity (PPV). Each measurement was 20 seconds in duration and all data were stored in memory for later retrieval.

## 8.0 RESULTS AND COMPARISON TO CRITERIA

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Results from the field program are organized by wind turbine type. For each wind turbine type, results are presented per location type (outdoor or indoor) with respect to applicable criteria. Results are presented for 1,000 feet from the nearest wind turbine. Data were also collected at 1,500 feet from the nearest wind turbine which showed lower sound levels. Therefore, wind turbines that met the criteria at 1,000 feet also met it at 1,500 feet. Data were collected under both high turbine output and moderate turbine output conditions, and low ground-level wind speeds (defined as sound power levels 2 or 3 dBA less than the maximum sound power levels). The sound level data under the moderate conditions were equivalent to or lower than the high turbine output scenarios, thus confirming the conclusions from the high output cases. A-weighted sound power levels presented in this section (used to describe turbine operation) were estimated from the actual measured power output (kW) of the wind turbines and the sound power levels as a function of wind speed presented in Table 6.0-1 plus an adjustment factor of 2 dBA (correction from reference values to guaranteed values).

Outdoor measurements are compared to criteria for audibility, for UK DEFRA disturbance using equivalent outdoor levels, for rattle and annoyance criteria as contained in ANSI S12.9 Part 4, and for perceptible vibration using equivalent outdoor levels from ANSI/ASA S12.2. Indoor measurements are compared to criteria for audibility, for UK DEFRA disturbance, and for suitability of bedrooms, hospitals and schools and perceptible vibration from ANSI/ASA S12.2.

### **8.0.1**      *Audibility*

The threshold of audibility criteria discussed in section 4.3.4 is used to evaluate wind turbine sound levels. The audibility of wind turbines both outdoors and indoors was examined.

### **8.0.2**      *UK DEFRA Disturbance Criteria*

The DEFRA one-third octave band sound pressure level  $L_{eq}$  criteria and procedures for assessing disturbance from low frequency noise (see section 4.3.2) were examined. The indoor criteria and equivalent outdoor criteria were compared to measured low frequency noise from wind turbines.

### **8.0.3**      *Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements*

The ANSI/ASA S12.2 interior perceptible vibration criteria were converted to equivalent outdoor criteria as discussed in section 4.2.3 and compared to the measured low frequency noise from wind turbines. In addition, measured data were compared to ANSI S12.9 Part 4 low frequency sound levels for minimal annoyance and for the threshold for beginning of rattles as described in section 4.2.2.

#### 8.0.4 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

The ANSI/ASA S12.2 interior perceptible vibration criteria and low frequency portions of the room criteria for evaluating the suitability of noises in bedrooms, hospitals and schools were compared to indoor measurements of low frequency noise from wind turbines. (See section 4.2.3.)

### 8.1 Siemens SWT-2.3-93

#### 8.1.1 Outdoor Measurements - Siemens SWT-2.3-93

Several periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 1,000 feet from the closest Siemens WTG. This site was actually part of a string of 15 WTGS, four of which were within 2,000 feet of the monitoring location. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.1-1

**Table 8.1-1 Summary of Operational Parameters – Siemens SWT-2.3-93 (Outdoor)**

Parameter	Sample #34	Sample #39
Distance to nearest WTG	1,000 feet	1,000 feet
Time of day	22:00-22:10	22:50-23:00
WTG power output	1,847 kW	1,608 kW
Sound power	107 dBA	106.8 dBA
Measured wind speed @ 2 m	3.3 m/s	3.4 m/s
L <sub>Aeq</sub>	49.4 dBA	49.6 dBA
L <sub>A90</sub>	48.4 dBA	48.6 dBA
L <sub>Ceq</sub>	63.5 dBC	63.2 dBC

##### 8.1.1.1 Outdoor Audibility

Figure 8.1-1 plots the one-third octave band sound levels ( $L_{eq}$ ) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound above 40 Hz may be audible depending on background sound levels.

##### 8.1.1.2 UK DEFRA Disturbance Criteria – Outdoor measurements

Figure 8.1-2 plots the one-third octave band sound levels ( $L_{eq}$ ) for both samples of high output conditions. The low frequency sound was “steady” according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met.

### 8.1.1.3 Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements

Figure 8.1-3 plots the 16, 31.5, and 63 Hz octave band sound levels ( $L_{eq}$ ) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB), and the 31.5 and 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4, and the 16 Hz sound level is within 1.5 dB of this level, which is an insignificant increase since the levels were not rapidly fluctuating.

### 8.1.2 Indoor Measurements - Siemens SWT-2.3-93

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from Siemens WTGs. In each house measurements were made in a room facing the wind turbines, and were made with either window open or closed. These residences are designated Homes "A" and "D" and were approximately 1,000 feet from the closest Siemens WTG. Both homes were near a string of multiple WTGS, four of which were within 2,000 feet of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.1-2.

**Table 8.1-2 Summary of Operational Parameters – Siemens SWT-2.3-93 (Indoor)**

Parameter	Home "A" (closed / open)	Home "D" (closed / open)
Distance to nearest WTG	1,060 feet	920 feet
Time of day	7:39-7:49 / 7:51-8:01	16:16-16:26 / 16:30 -16:40
WTG power output	1,884 kW / 1564 kW	2,301 kW / 2299 kW
Sound power	107 dBA / 106.7 dBA	107 dBA / 107 dBA
Measured wind speed @ 2 m	3.2 m/s / 3.7 m/s	9.6 m/s / 8.8 m/s
$L_{Aeq}$	33.8 dBA / 38.1 dBA	35.0 dBA / 36.7 dBA
$L_{A90}$	28.1 dBA / 36.8 dBA	29.6 dBA / 31.2 dBA
$L_{Ceq}$	54.7 dBC / 57.1 dBC	52.8 dBC / 52.5 dBC

#### 8.1.2.1 Indoor Audibility

Figure 8.1-4a plots the indoor one-third octave band sound levels ( $L_{eq}$ ) for Home "A", and Figure 8.1-4b plots the indoor one-third octave band sound levels for Home "D". The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at or above 50 Hz may be audible depending on background sound levels.



### 8.1.2.2 UK DEFRA Disturbance Criteria – Indoor Measurements

Figure 8.1-5a plots the indoor one-third octave band sound levels ( $L_{eq}$ ) for Home “A”. The low frequency sound was “steady” according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met. Figure 8.1-5b plots the indoor one-third octave band sound levels ( $L_{eq}$ ) for Home “D”. According to DEFRA procedures, the low frequency sound was not “steady” and therefore the data were compared to both criteria. The results show the DEFRA disturbance criteria were met for steady low frequency sounds, the DEFRA criteria were met for unsteady low frequency sounds except for the 125 Hz band, which was within 1 dB, which is an insignificant difference.

### 8.1.2.3 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

Figure 8.1-6a plots the indoor 16 Hz to 125 Hz octave band sound levels ( $L_{eq}$ ) for Home “A”, and Figure 8.1-6b plots the indoor 16 Hz to 125 Hz octave band sound levels ( $L_{eq}$ ) for Home “D”. The results show the ANSI/ASA S12.2 low frequency criteria were easily met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency criteria for bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

## 8.2 GE 1.5sle

### 8.2.1 *Outdoor Measurements - GE 1.5sle*

Several periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 1,000 feet from the closest GE 1.5 sle WTG. This site was actually part of a string of more than 30 WTGS, four of which were within 2,000 feet of the monitoring location. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters for these measurements are listed in Table 8.2-1.

**Table 8.2-1 Summary of Operational Parameters – GE 1.5sle (Outdoor)**

Parameter	Sample #46	Sample #51
Distance to nearest WTG	1,000 feet	1,000 feet
Time of day	23:10-23:20	00:00-00:10
WTG power output	1,293 kW	1,109 kW
Sound power	106 dBA	106 dBA
Measured wind speed @ 2 m	4.1 m/s	3.3 m/s
L <sub>Aeq</sub>	50.2 dBA	50.7 dBA
L <sub>A90</sub>	49.2 dBA	49.7 dBA
L <sub>Ceq</sub>	62.5 dBC	62.8 dBC

### 8.2.1.1 Outdoor Audibility

Figure 8.2-1 plots the one-third octave band sound levels ( $L_{eq}$ ) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 31.5 - 40 Hz may be audible depending on background sound levels.

### 8.2.1.2 UK DEFRA Disturbance Criteria – Outdoor measurements

Figure 8.2-2 plots the one-third octave band sound levels ( $L_{eq}$ ) for both samples of high output conditions. The low frequency sound was “steady” according to DEFRA procedures, and the results show the low frequency sound meet or are within 1 dB of outdoor equivalent DEFRA disturbance criteria.

### 8.2.1.3 Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements

Figure 8.2-3 plots the 16, 31.5, and 63 Hz octave band sound levels ( $L_{eq}$ ) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB), and the 16, 31.5, 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4.

## 8.2.2 Indoor Measurements - GE 1.5sle

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from GE 1.5sle WTGs. In each house, measurements were made in a room facing the wind turbines, and were made with window either open or closed. These residences are designated Homes “B” and “C” and were approximately 1,000 feet from the closest Siemens WTG. Operational conditions were maximum turbine noise and high ground

winds at Home “B”, and within 1.5 dBA of maximum turbine noise and high ground level winds at Home “C”. Home “B” was near a string of multiple WTGs, four of which were within 2,000 feet of the house, while Home “C” was at the end of a string of WTGs, two of which were within 2,000 feet of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.2-2.

**Table 8.2-2 Summary of Operational Parameters – GE 1.5sle (Indoor)**

Parameter	Home “B” (closed / open)	Home “C” (closed / open)
Distance to nearest WTG	950 feet	1,025 feet
Time of day	9:29-9:39 / 9:40-9:50	11:49-11:59 / 12:00-12:10
WTG power output	1,017 kW / 896 kW	651 kW / 632 kW
Sound power	106 dBA / 105.8 dBA	104.7 dBA / 104.6 dBA
Measured wind speed @ 2 m	6.2 m/s / 6.8 m/s	6.4 m/s / 5.9 m/s
$L_{Aeq}$	27.1 dBA / 36.0 dBA	33.6 dBA / 39.8 dBA
$L_{A90}$	23.5 dBA / 33.7 dBA	27.6 dBA / 34.2 dBA
$L_{Ceq}$	47.1 dBC / 54.4 dBC	50.6 dBC / 55.1 dBC

### 8.2.2.1 Indoor Audibility

Figure 8.2-4a plots the indoor one-third octave band sound levels ( $L_{eq}$ ) for Home “B”, and Figure 8.2-4b plots the indoor one-third octave band sound levels for Home “C”. The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 63 Hz may be audible depending on background sound levels.

### 8.2.2.2 UK DEFRA Disturbance Criteria – Indoor Measurements

Figure 8.2-5a plots the indoor one-third octave band sound levels ( $L_{eq}$ ) for Home “B”, and Figure 8.2-5b plots the indoor one-third octave band sound levels ( $L_{eq}$ ) for Home “C”. The results show the DEFRA disturbance criteria were met for steady and non-steady low frequency sounds.

### 8.2.2.3 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

Figure 8.2-6a plots the indoor 16 Hz to 125 Hz octave band sound levels ( $L_{eq}$ ) for Home “B”, and Figure 8.2-6b plots the indoor 16 Hz to 125 Hz octave band sound levels ( $L_{eq}$ ) for Home “C”. The results show the ANSI/ASA S12.2 low frequency criteria were met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency criteria for

bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

### 8.3 Noise Reduction from Outdoor to Indoor

Simultaneous outdoor and indoor measurements were made at four residences within the Horse Hollow Wind Farm to determine noise reductions of the homes for comparison to that used in the determination of equivalent outdoor criteria for indoor criteria, such as ANSI/ASA S12.2 and DEFRA. Indoor measurements were made with windows open and closed. Tables 8.1-2 and 8.2-2 list the conditions of measurement for these houses.

The outdoor sound level data at Home “D” was heavily influenced by high ground winds – the measured levels were higher due to the effect of the wind on the microphone or the measurement of wind effect noise; therefore the data from Home “D” was not used in the comparison of noise reduction, since it would over estimate actual noise reduction.

Figures 8.3-1a and 8.3-1b present the measured one-third octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in these same figures are the one-third octave noise reductions used in Section 4 of this report to obtain equivalent outdoor criteria for the indoor DEFRA criteria (“Table 4.3-1 Noise Reduction - Open Window”). It can be seen that for the window closed condition in Figure 8.3-1a, the measured noise reductions for all houses were greater than that used in our analysis as described in Section 4. For the open window case, the average of the three homes has a greater noise reduction than used in Section 4 and all houses at all frequencies have higher values with one minor exception. Only Home “A” at 25 Hz had a lower noise reduction (3dB), and this difference is not critical since the measured indoor sounds at 25 Hz at each of these home was significantly lower than the indoor DEFRA criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 1000 feet under high output/high noise levels met the equivalent outdoor DEFRA criteria at 25 Hz.

Table 8.3-1 presents the measured octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in Table 8.3-1 are the octave band noise reductions used in Table 4.2-2 of this report to obtain equivalent outdoor criteria for the indoor ANSI/ASA S12.2 criteria for perceptible vibration. It can be seen that for the window closed condition, the measured noise reductions for all houses were greater than that used in our analysis as described in Section 4. For the open window case, the average of the three homes has a greater noise reduction than used in Section 4 and all houses at all frequencies have higher values with one minor exception. Only Home “A” at 31 Hz (which contains the 25 Hz one-third octave band) had a lower noise reduction (3dB), and this difference is not critical since the measured indoor sounds at 31 Hz at each of these homes was significantly lower than the indoor ANSI/ASA S12.2 criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 1000 feet under high output/high noise levels met the equivalent outdoor ANSI/ASA S12.2 criteria at 31 Hz.

**Table 8.3-1 Summary of Octave Band Noise Reduction – Interior Measurements**

Home	Wind Turbine	Windows	16 Hz	31.5 Hz	63 Hz
A	Siemens SWT-2-3-93	Closed	5	6	16
A	Siemens SWT-2-3-93	Open	4	3	12
B	GE 1.5 sle	Closed	20	22	22
B	GE 1.5 sle	Open	13	17	18
C	GE 1.5 sle	Closed	13	14	19
C	GE 1.5 sle	Open	8	13	17
Table 4.2-2 Noise Reduction		Open	3	6	9

#### 8.4 Ground-Borne Vibration

Seven sets of ground-borne vibration measurements were made from Siemens 2.3 and GE 1.5sle wind turbines. The maximum ground-borne vibration RMS particle velocities were 0.071 mm/second (0.0028 inches/second) in the 8 Hz one-third octave band. This was measured 1000 feet downwind from a GE 1.5sle WTG under maximum power output and high wind at the ground. The background ground-borne vibration RMS particle velocity at the same location approximately 20 minutes beforehand was 0.085 mm/sec. Both of these measurements meet ANSI S2.71 recommendations for perceptible vibration in residences during night time hours. Soil conditions were soft earth representative of an active agricultural use. These vibration levels are nearly three orders of magnitude below the level of 0.75 inches/second set to prevent damage to residential structures. No perceptible vibration was felt from operation of the wind turbines. Measurements at the other sites and as close as 400 feet were significantly lower than the above measurements under high wind conditions.

Figure 8.1-1 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to Audibility Criteria

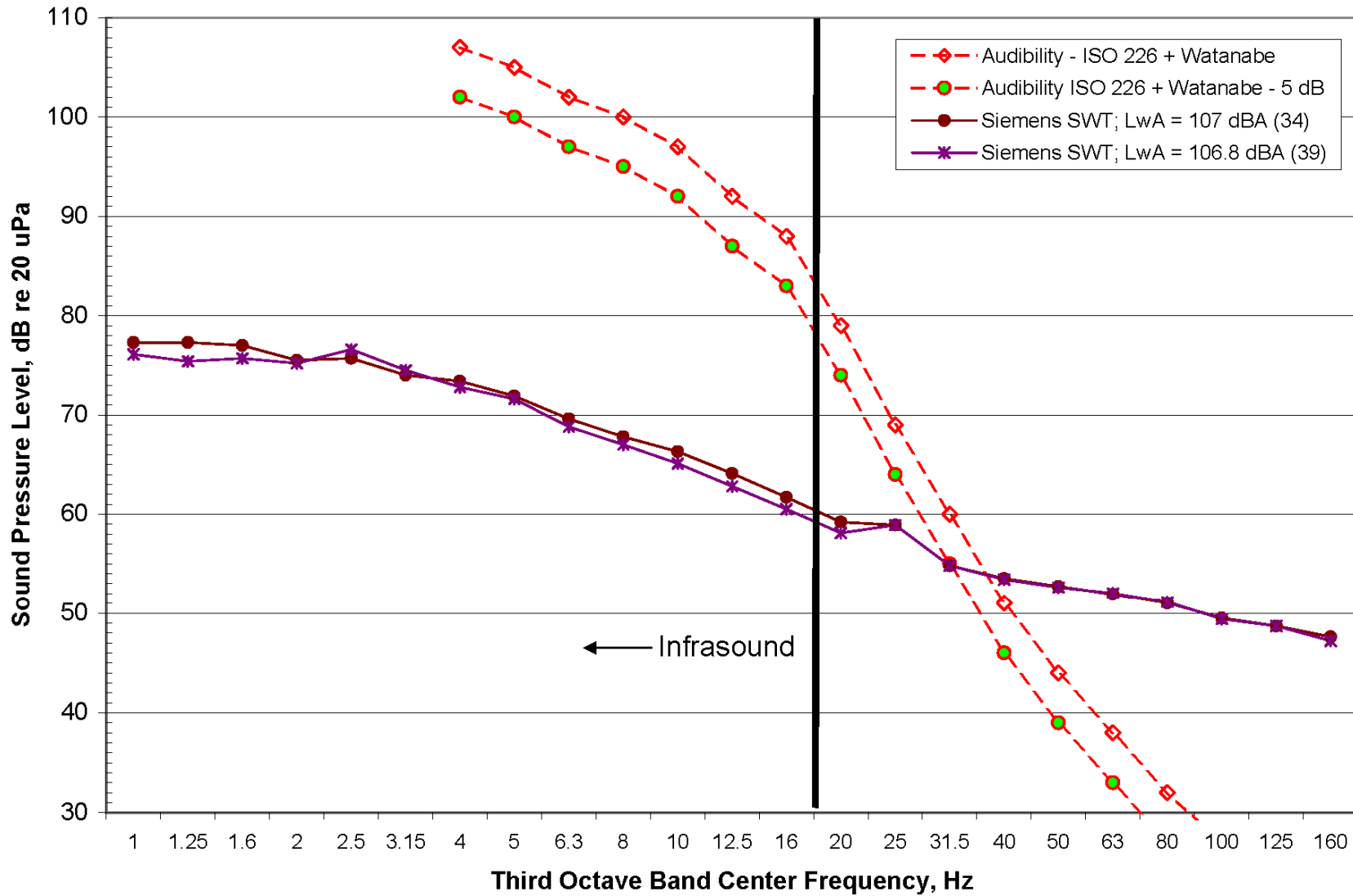


Figure 8.1-2 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to outdoor equivalent DEFRA Criteria

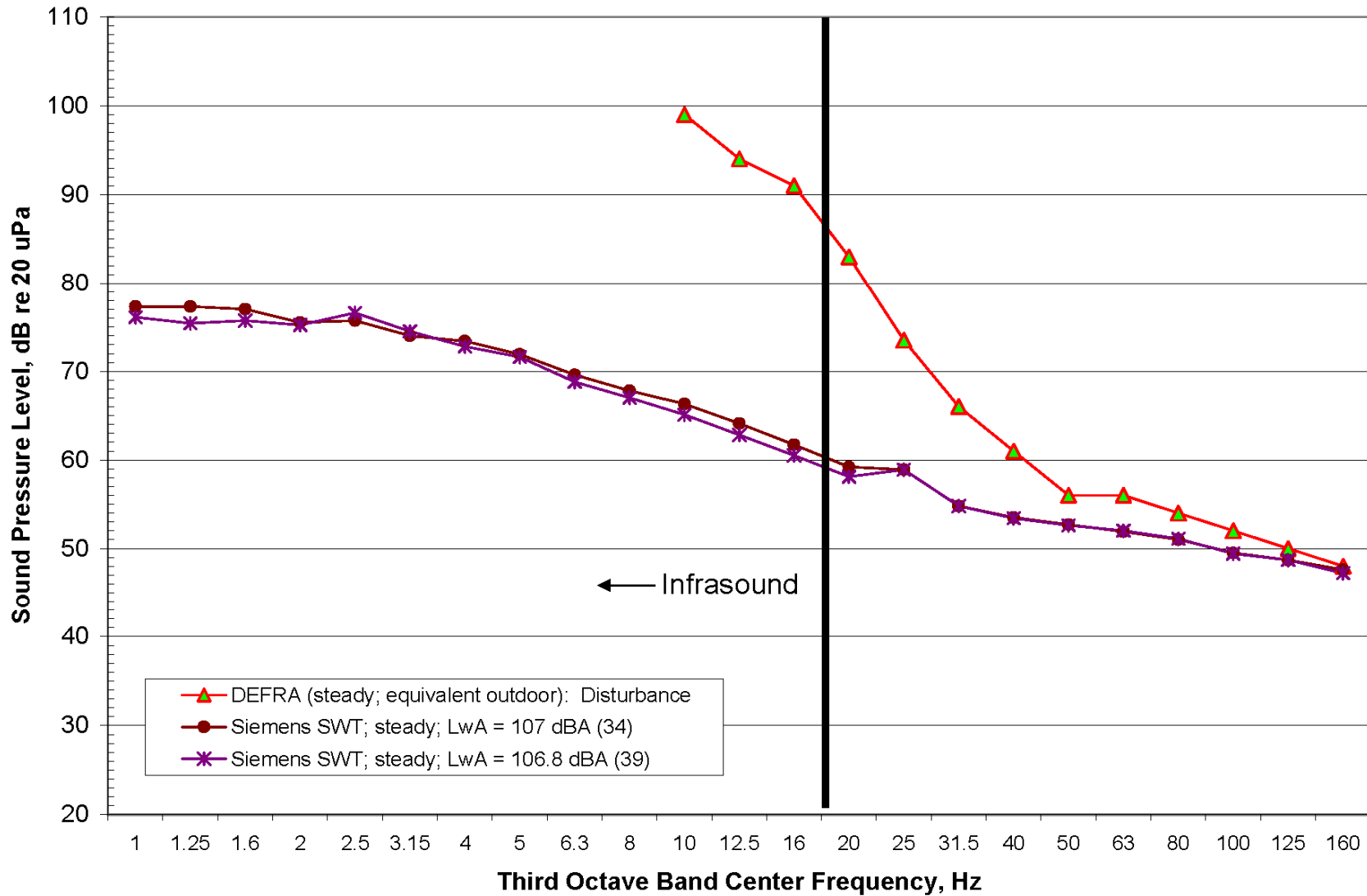


Figure 8.1-3 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to ANSI Criteria

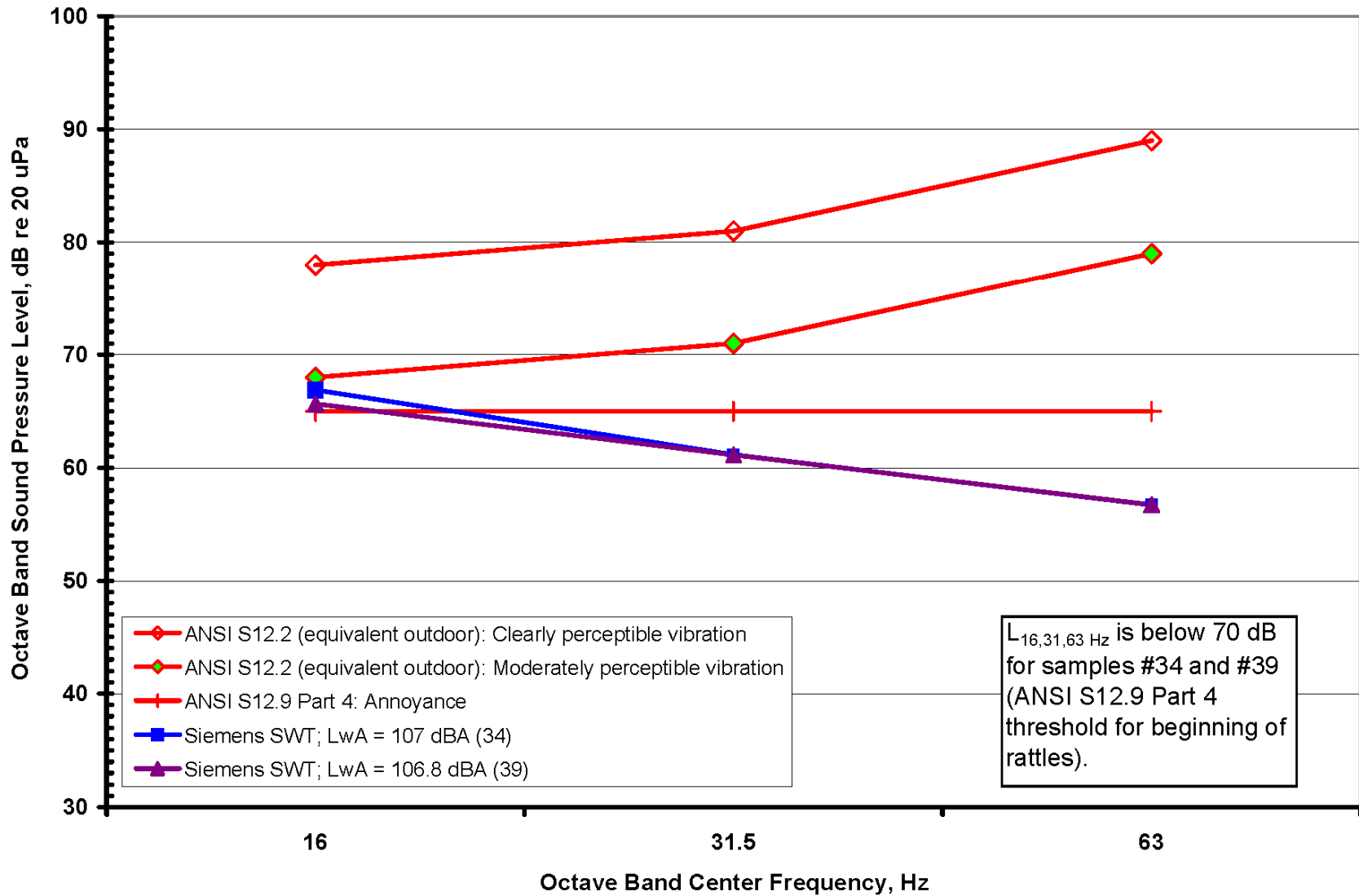




Figure 8.1-4a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to Audibility Criteria (Home "A")

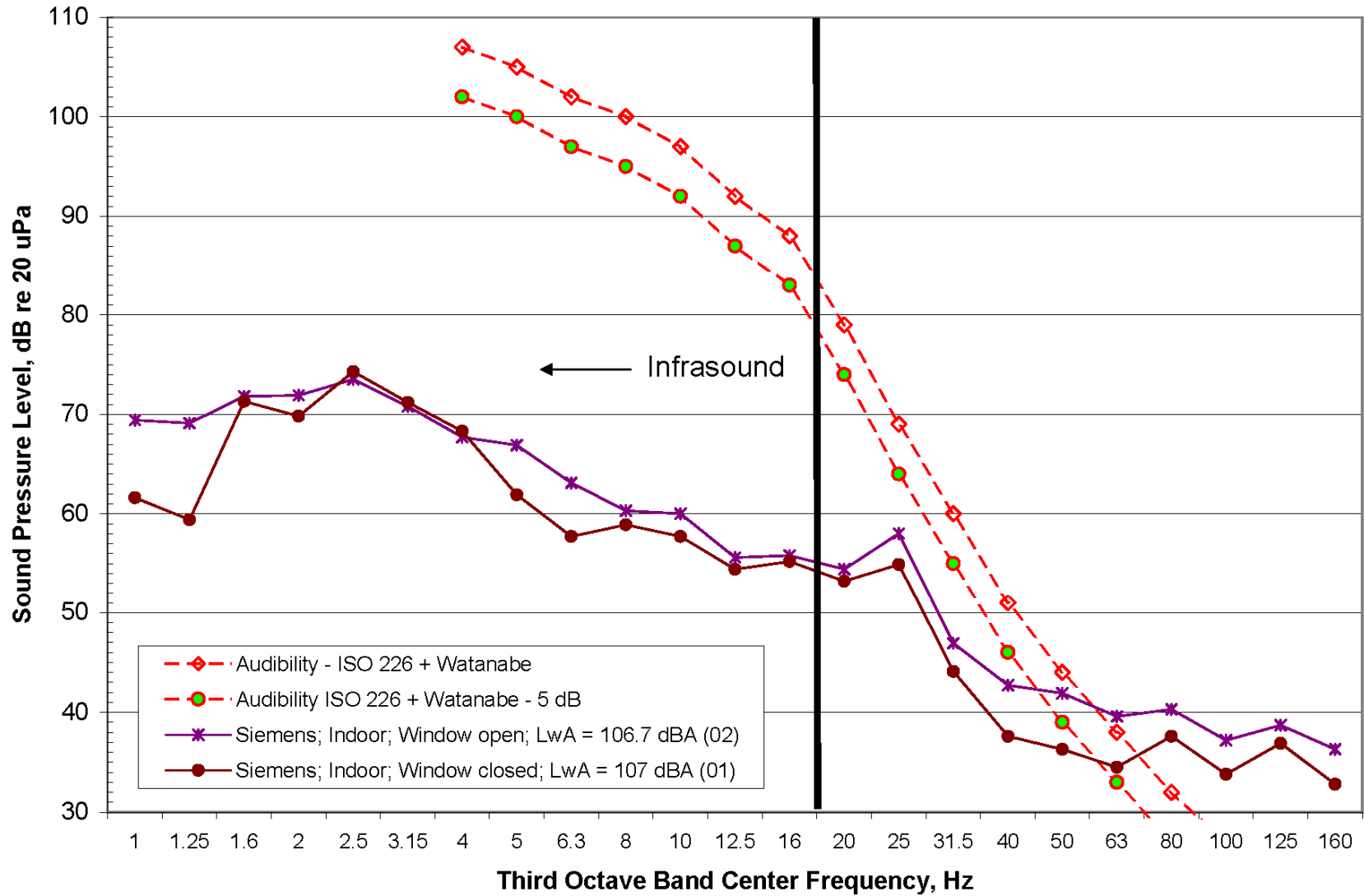


Figure 8.1-4b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to Audibility Criteria (Home "D")

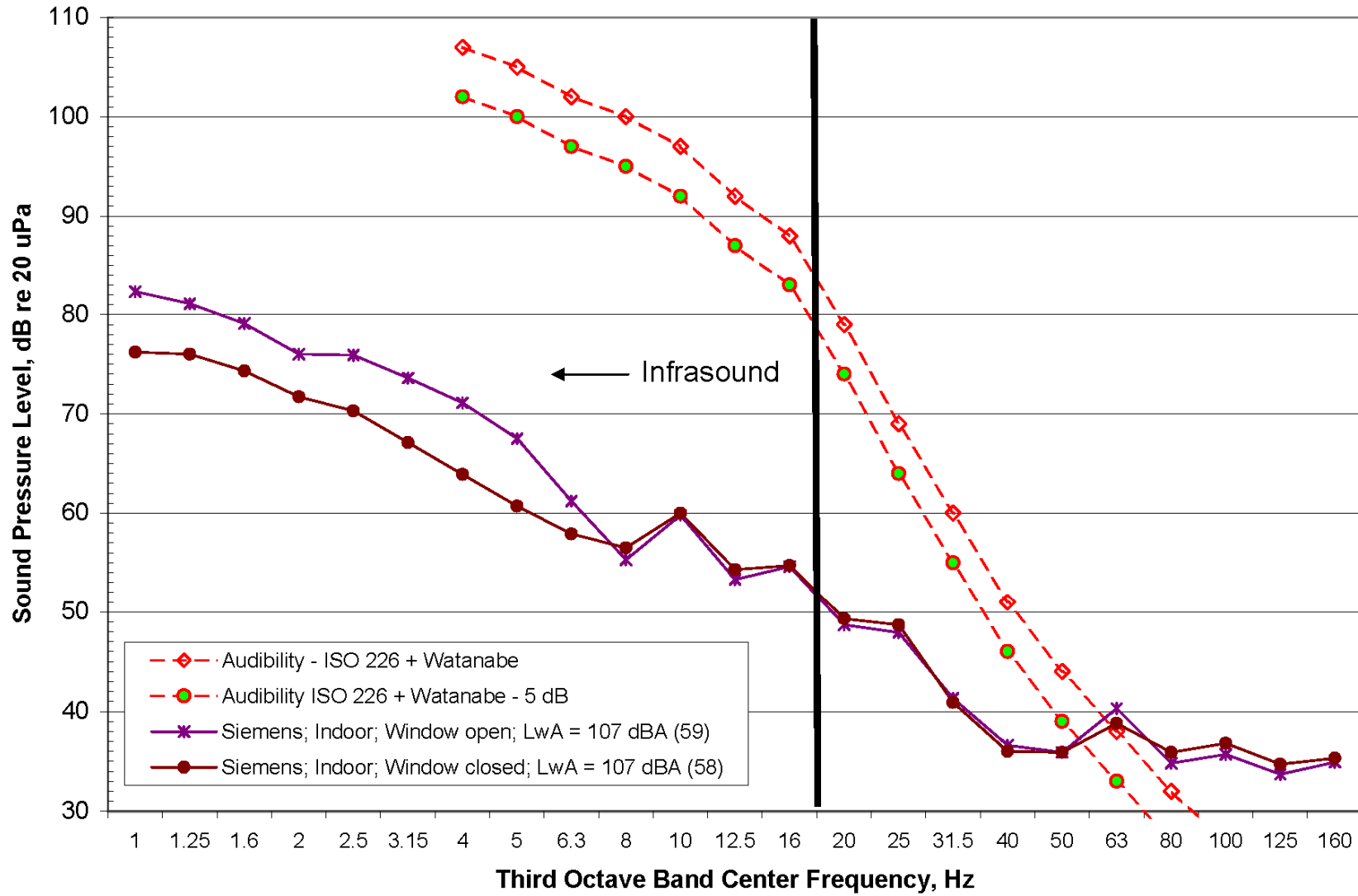


Figure 8.1-5a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to DEFRA Criteria (Home "A")

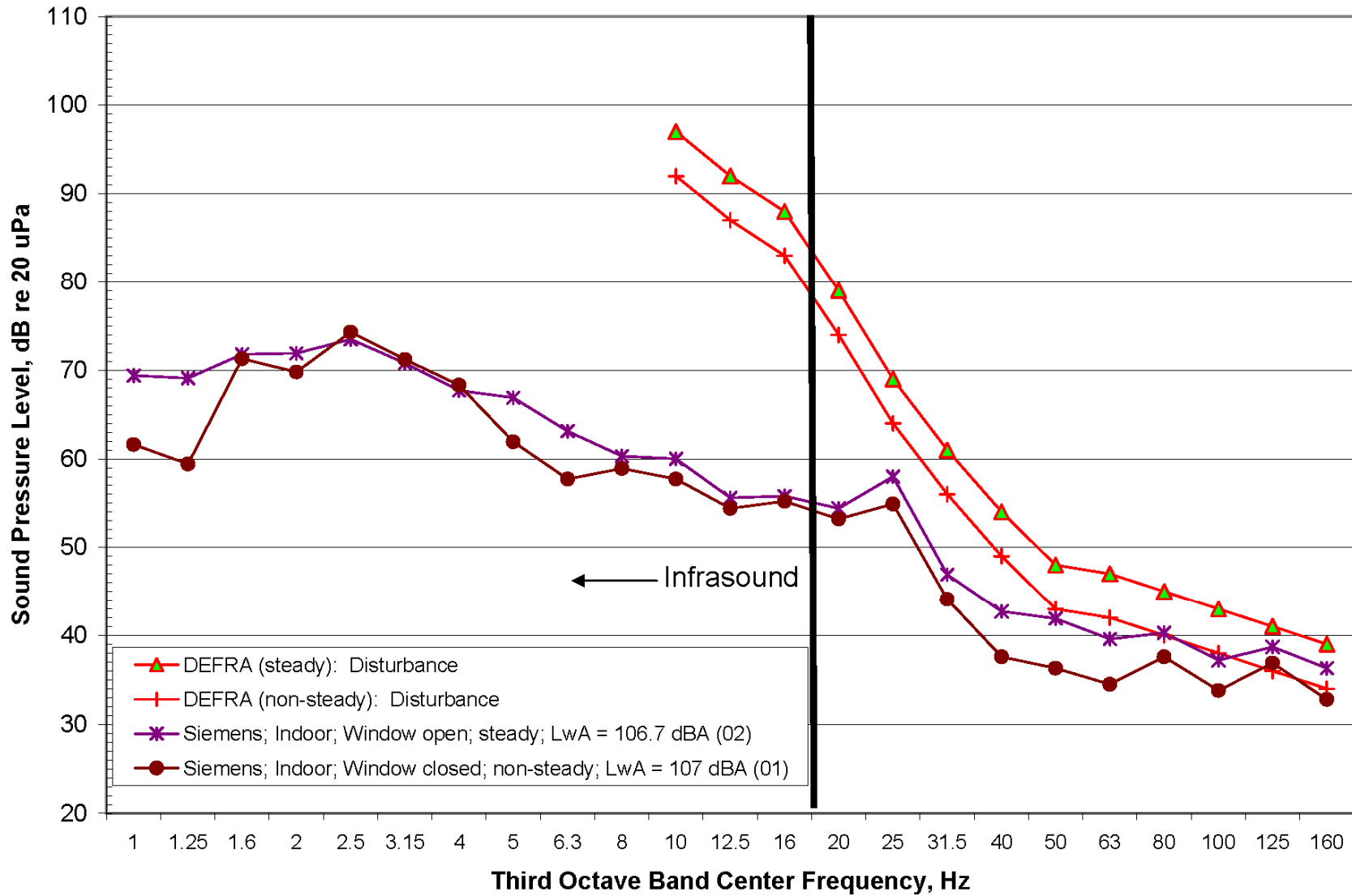


Figure 8.1-5b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to DEFRA Criteria (Home "D")

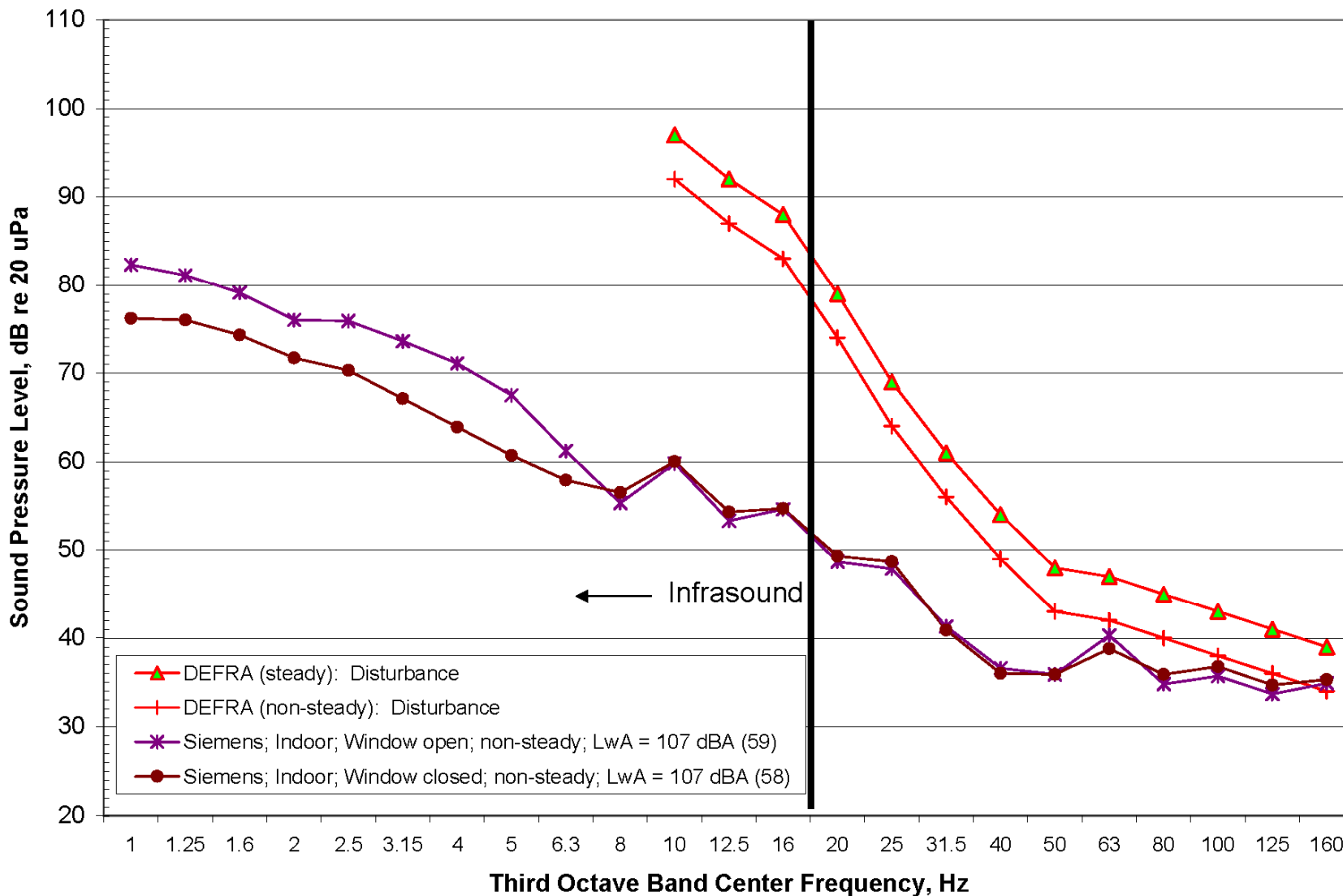


Figure 8.1-6a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to ANSI 12.2 Criteria (Home "A")

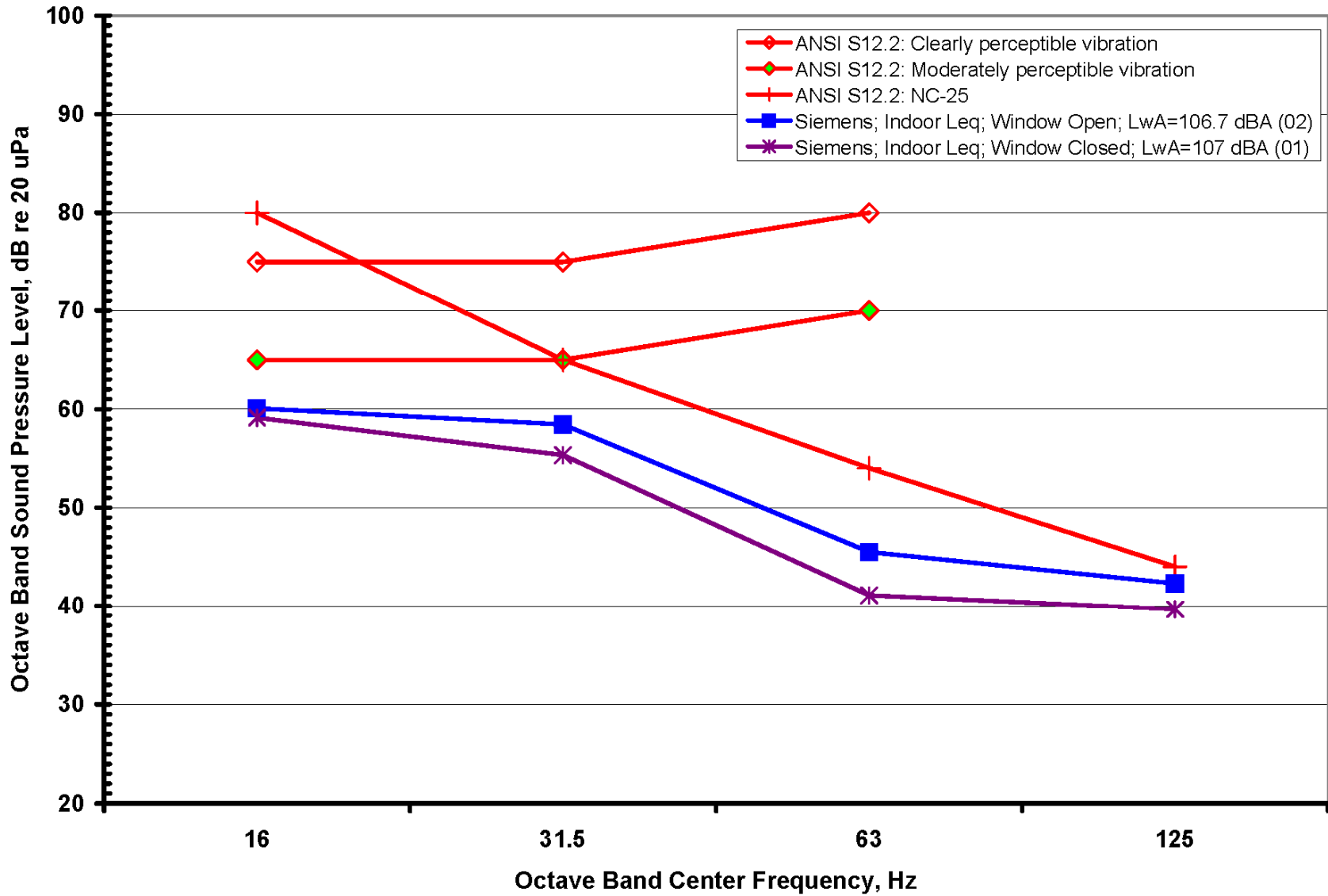


Figure 8.1-6b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to ANSI 12.2 Criteria (Home "D")

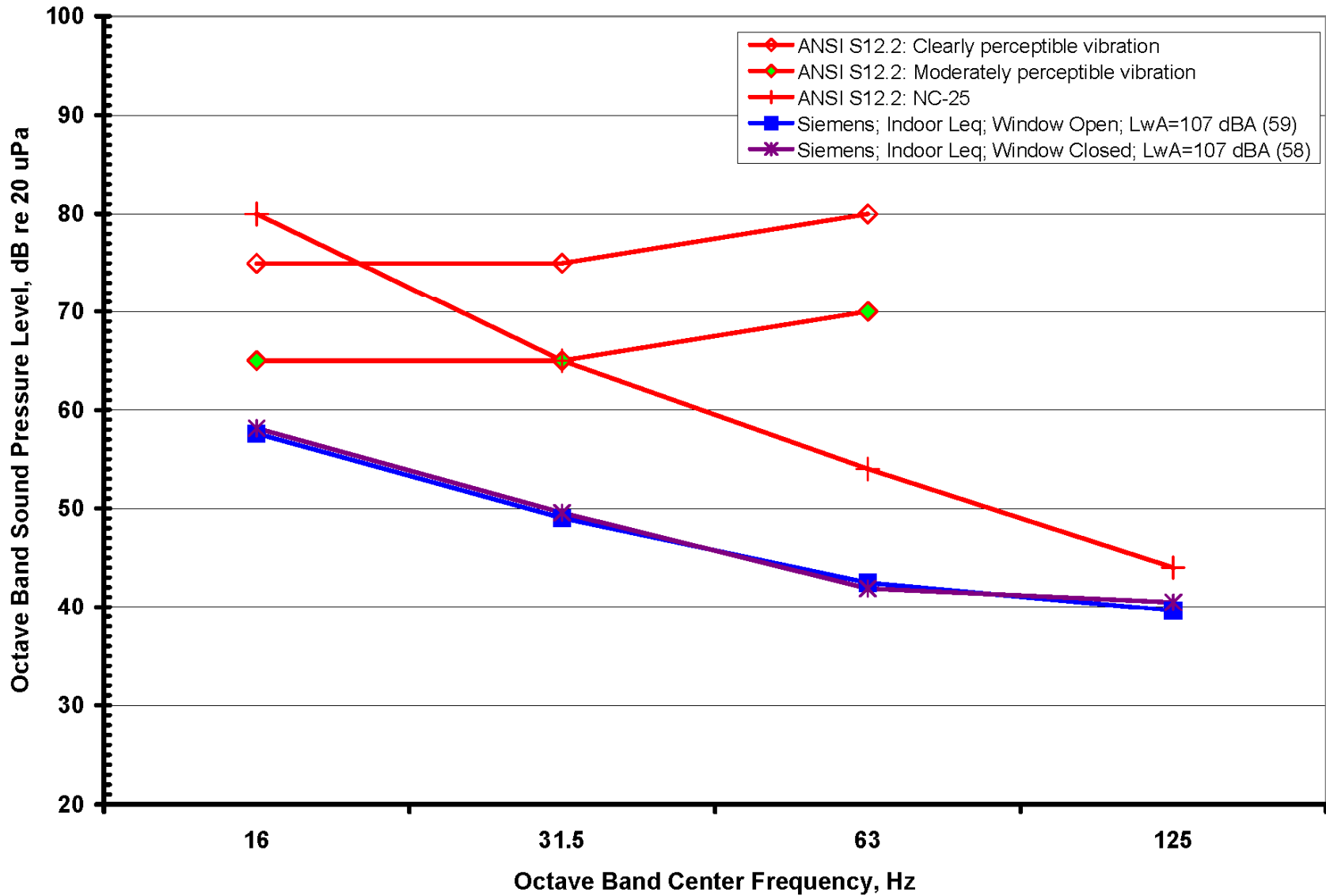


Figure 8.2-1 GE 1.5sle Wind Turbine Outdoor Sound Levels at 1000 feet compared to Audibility Criteria

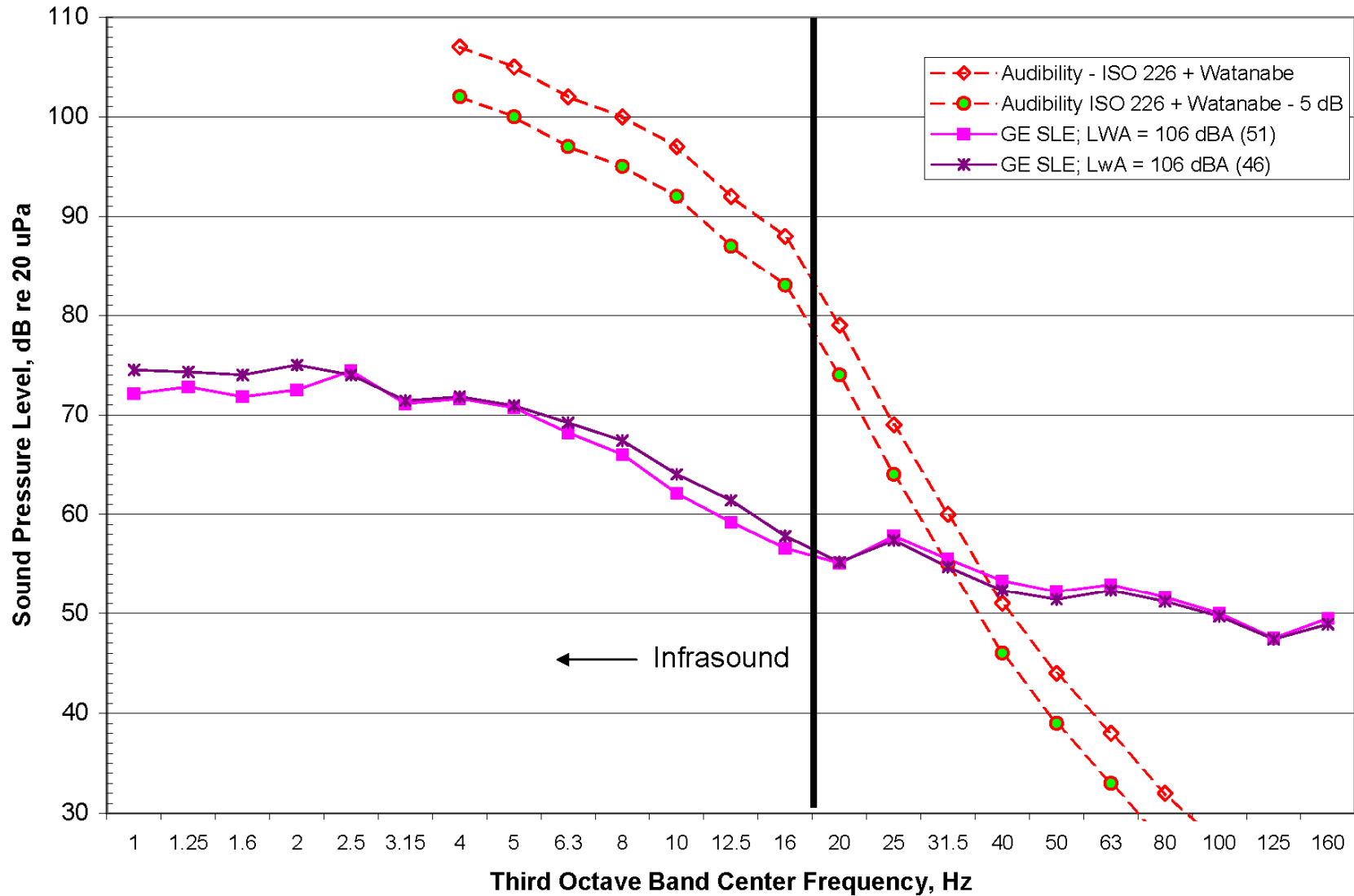


Figure 8.2-2 GE 1.5sl Wind Turbine Outdoor Sound Levels at 1000 feet compared to outdoor equivalent DEFRA Criteria

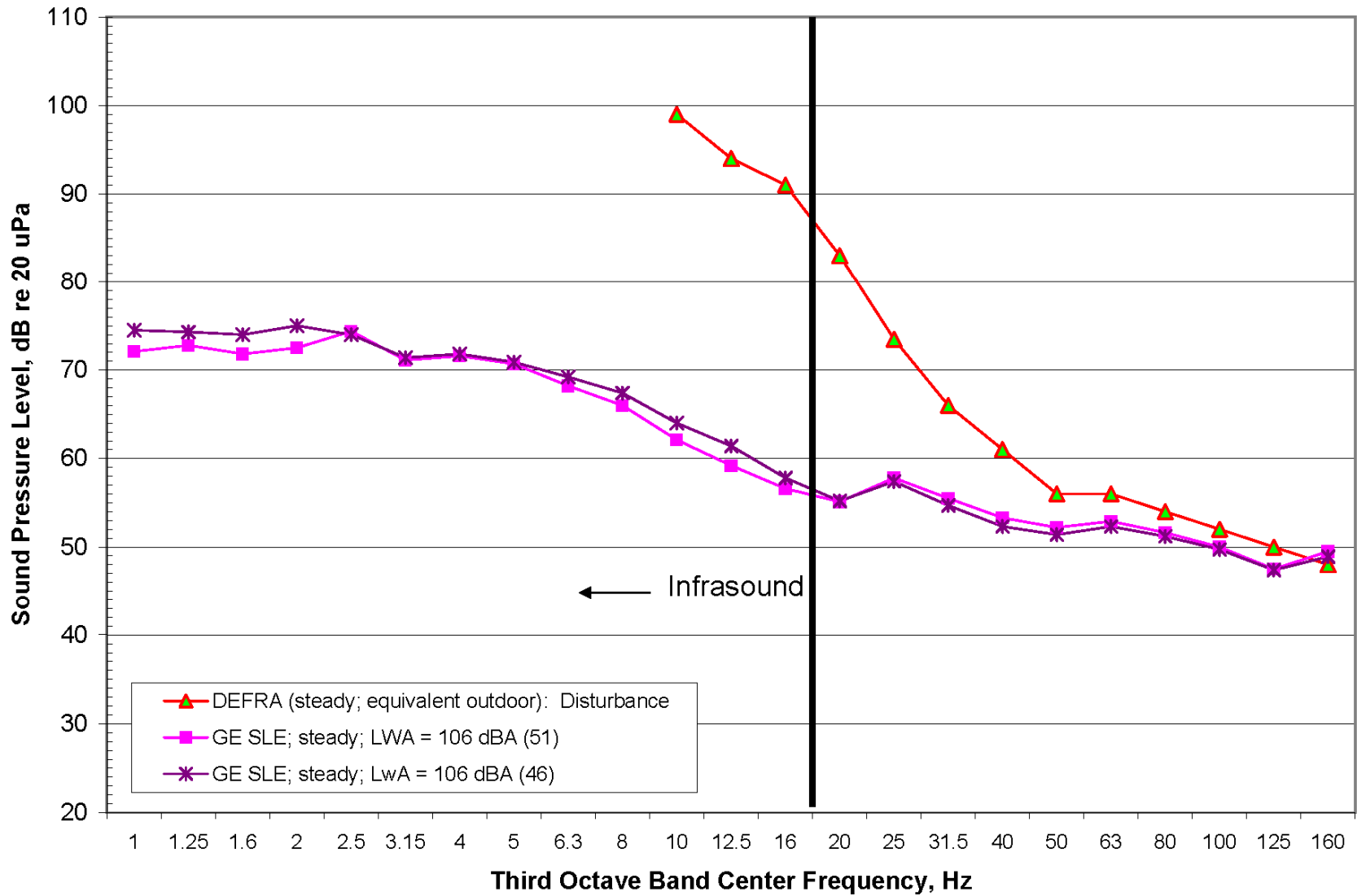




Figure 8.2-3 GE 1.5sle Wind Turbine Outdoor Sound Levels at 1000 feet compared to ANSI Criteria

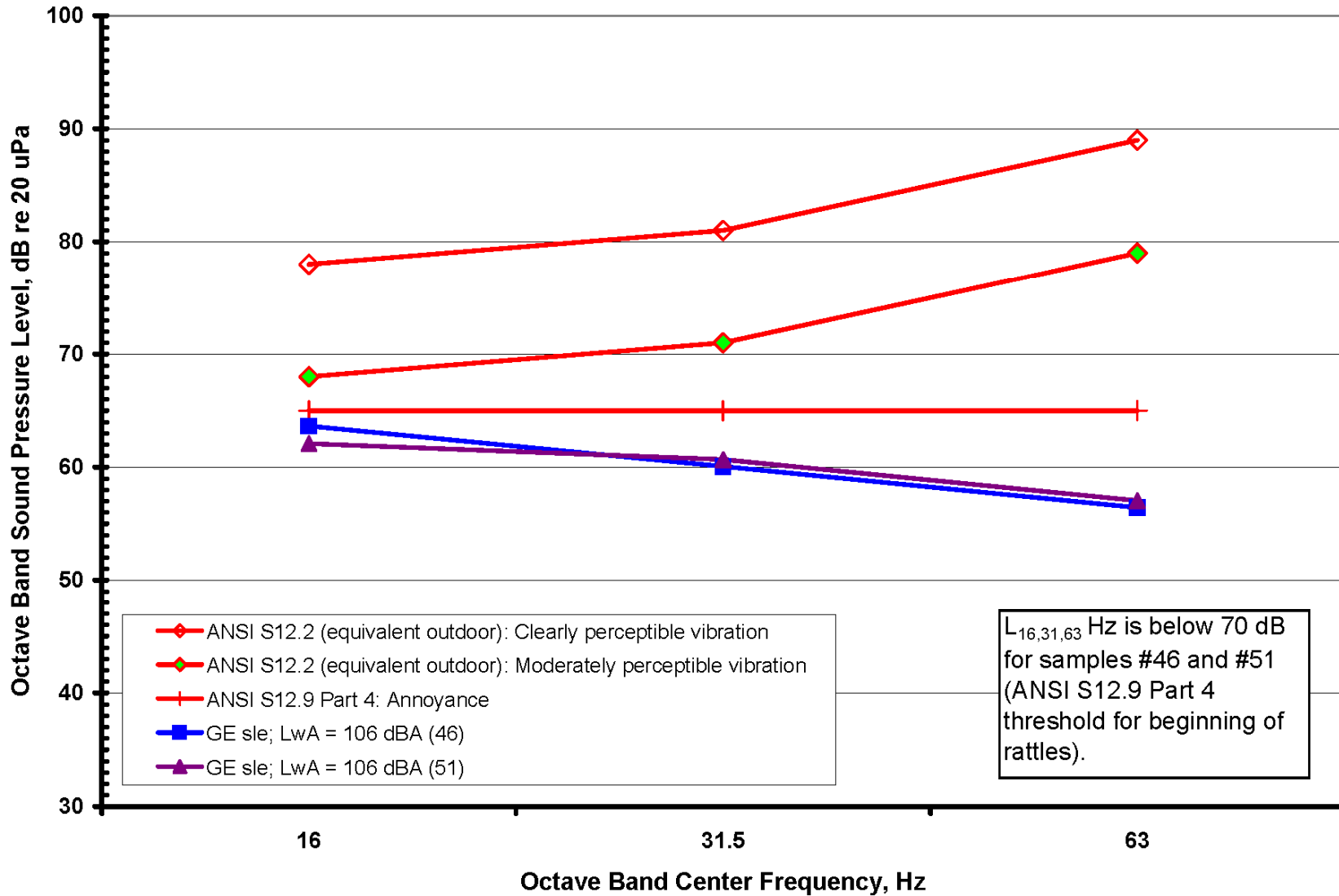


Figure 8.2-4a GE 1.5sle Wind Turbine Indoor Sound Levels at 950 feet compared to Audibility Criteria (Home "B")

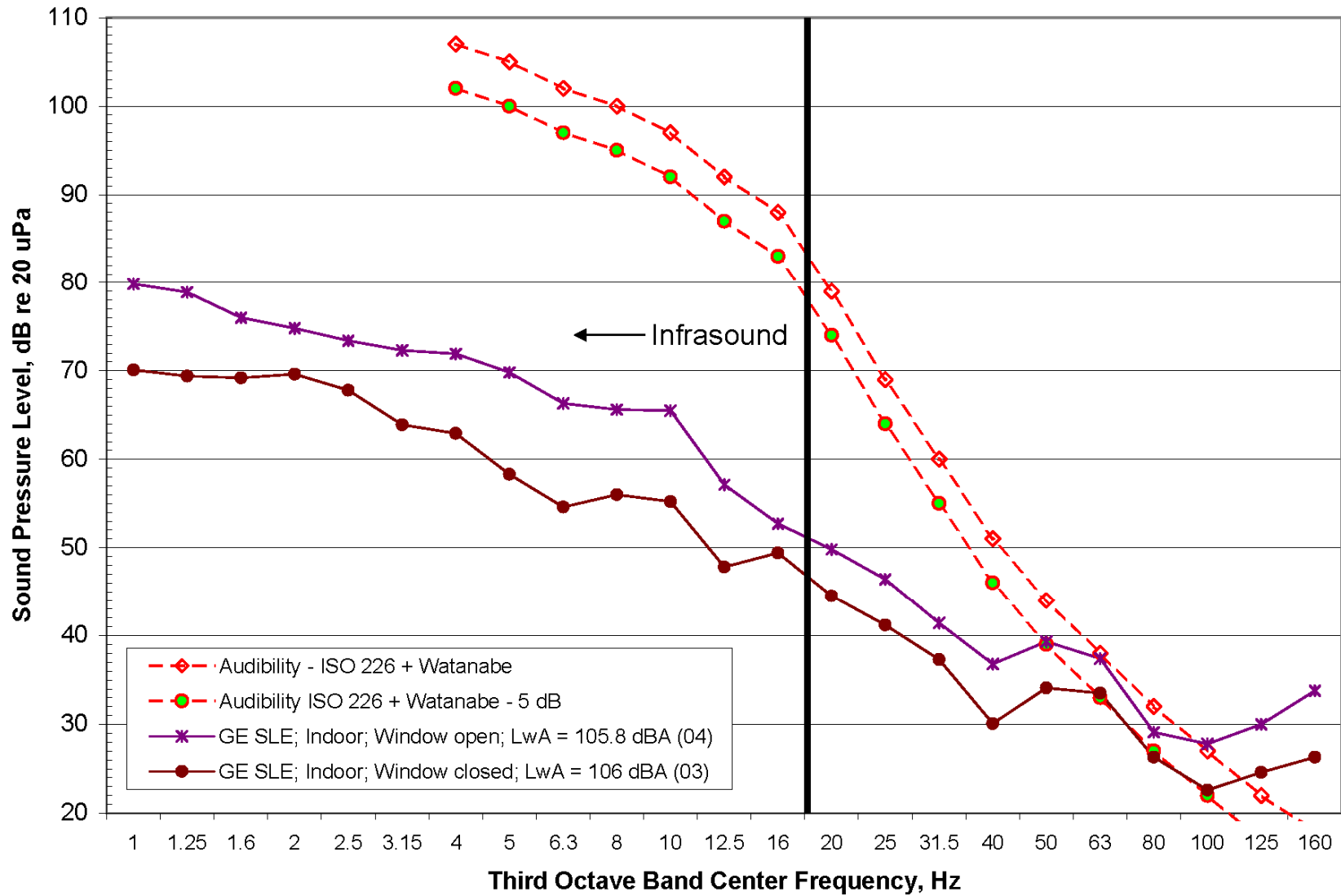


Figure 8.2-4b GE 1.5le Wind Turbine Indoor Sound Levels at 1025 feet compared to Audibility Criteria (Home "C")

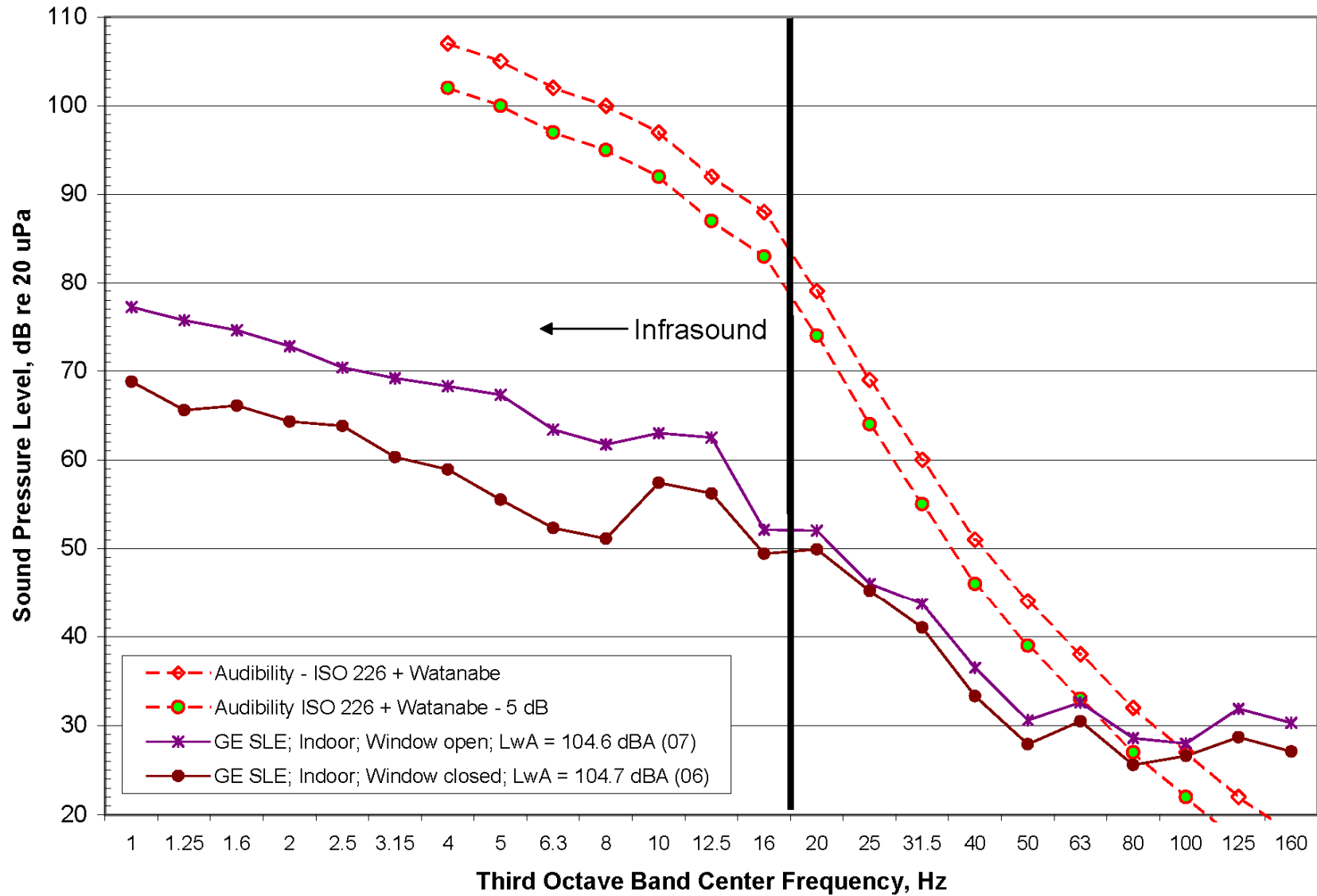


Figure 8.2-5a GE 1.5sle Wind Turbine Indoor Sound Levels at 950 feet compared to DEFRA Criteria (Home "B")

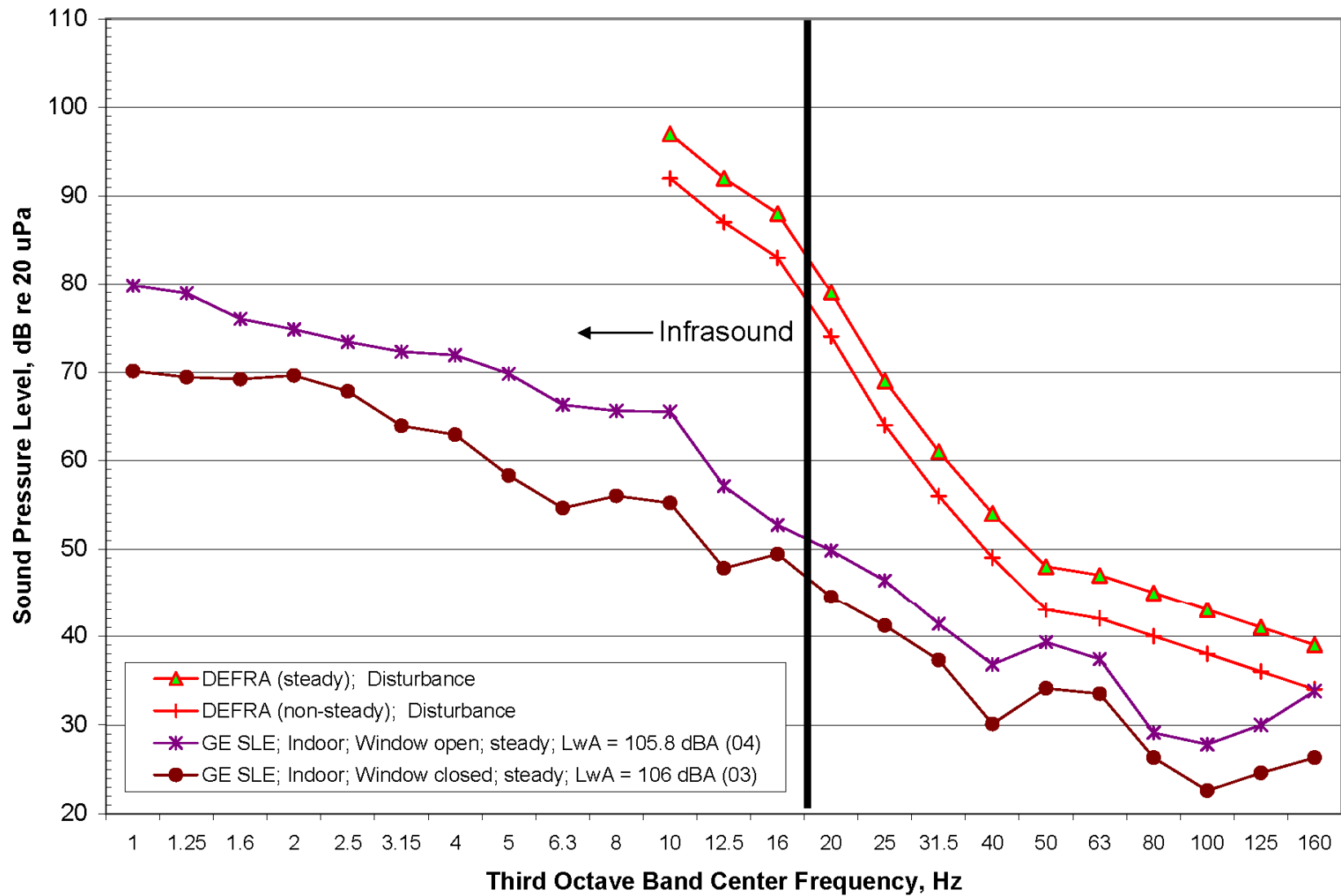


Figure 8.2-5b GE 1.5sle Wind Turbine Indoor Sound Levels at 1025 feet compared to DEFRA Criteria (Home "C")

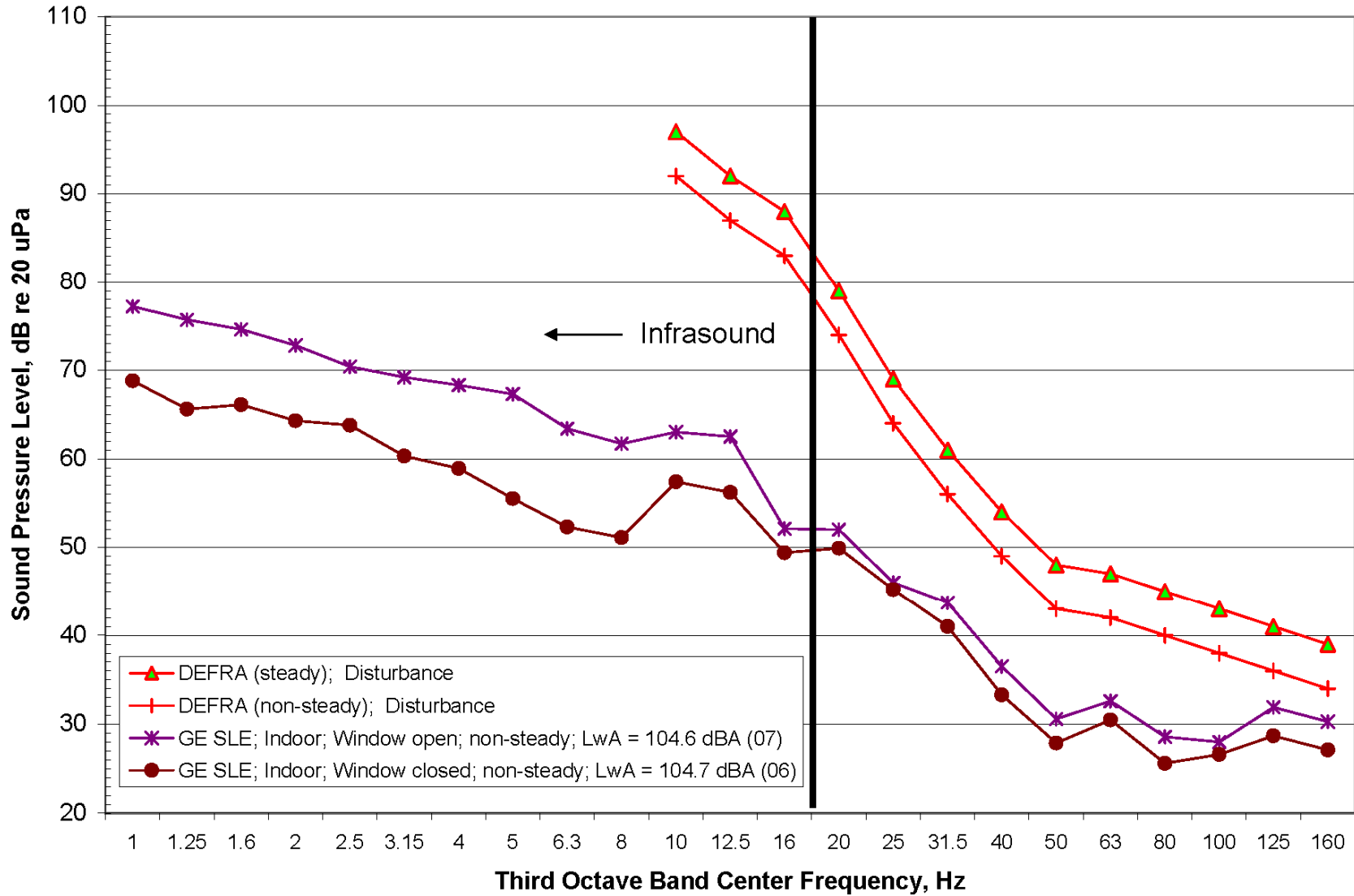


Figure 8.2-6a GE 1.5 sle Wind Turbine Indoor Sound Levels at 950 feet compared to ANSI 12.2 Criteria (Home "B")

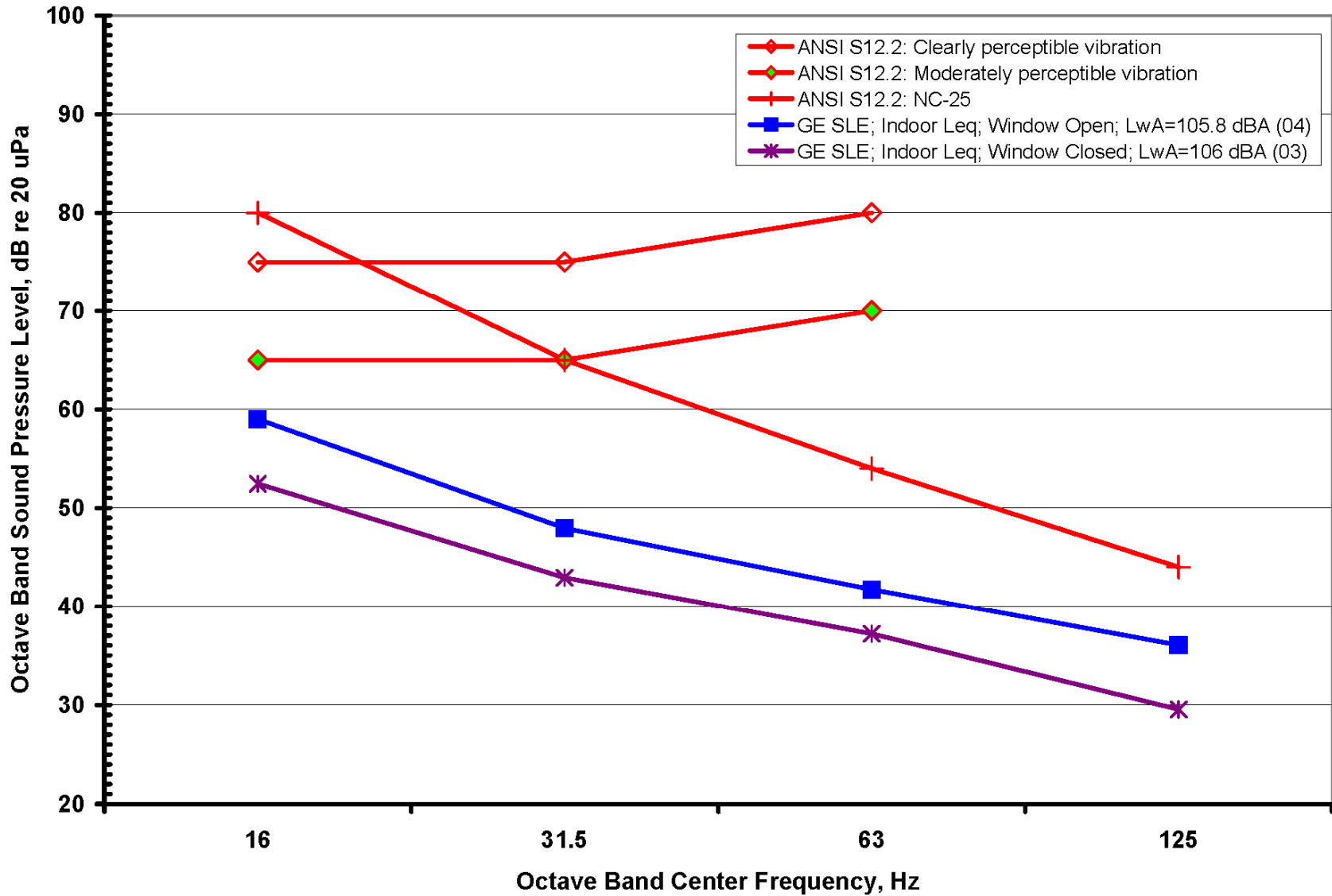


Figure 8.2-6b GE 1.5 sle Wind Turbine Indoor Sound Levels at 1025 feet compared to ANSI 12.2 Criteria (Home "C")

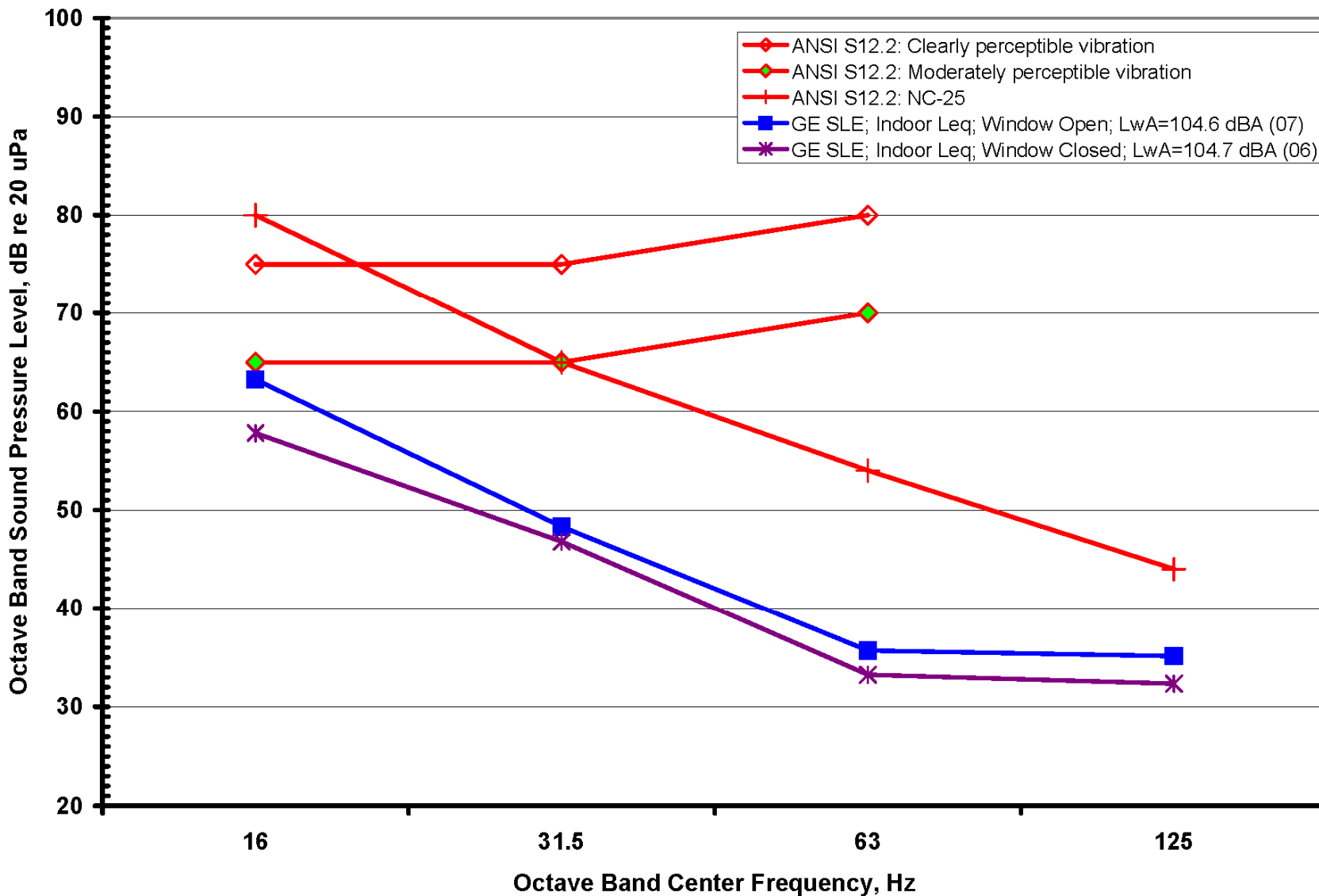


Figure 8.3-1a One-Third Octave Band Interior Noise Reduction – Windows Closed

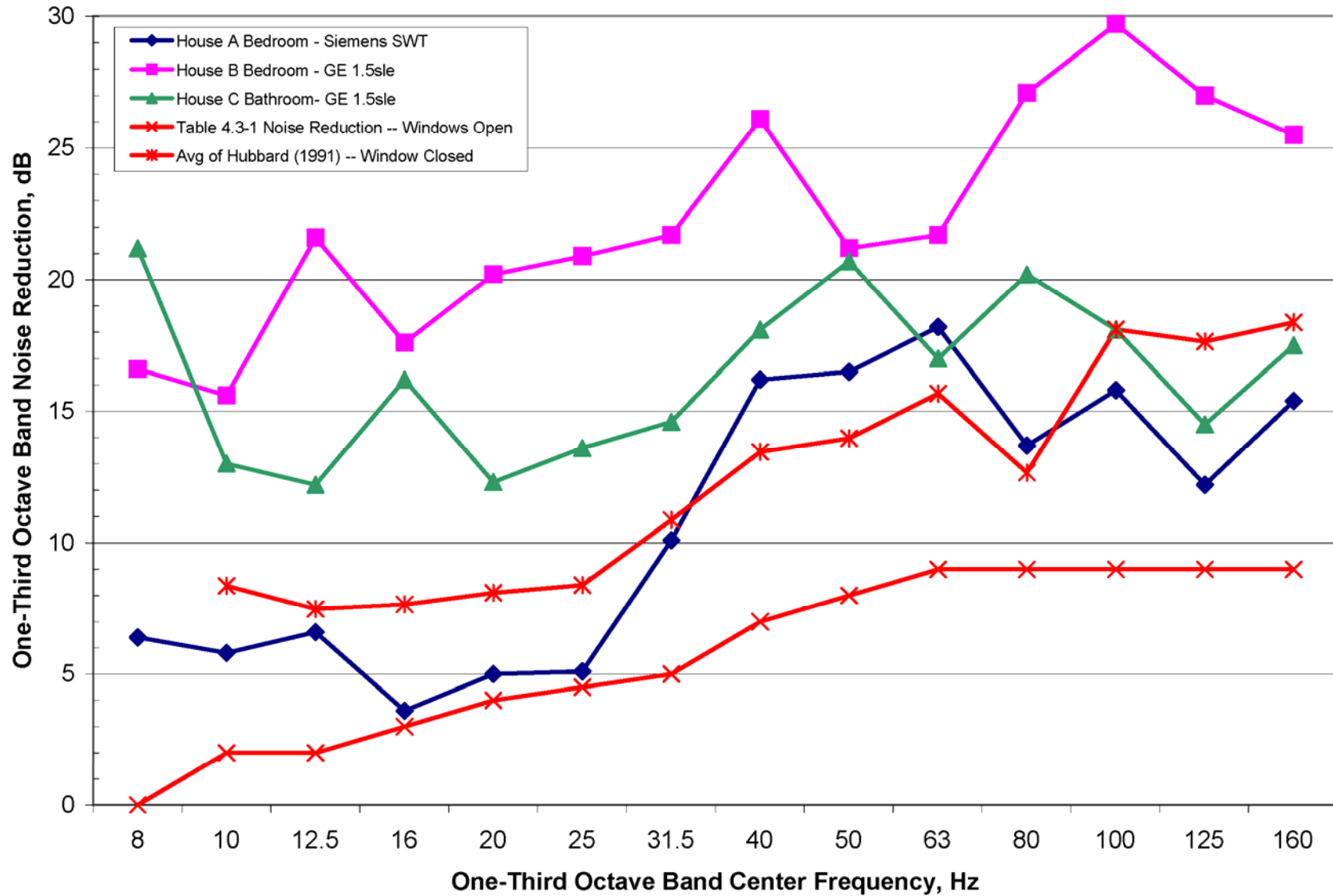
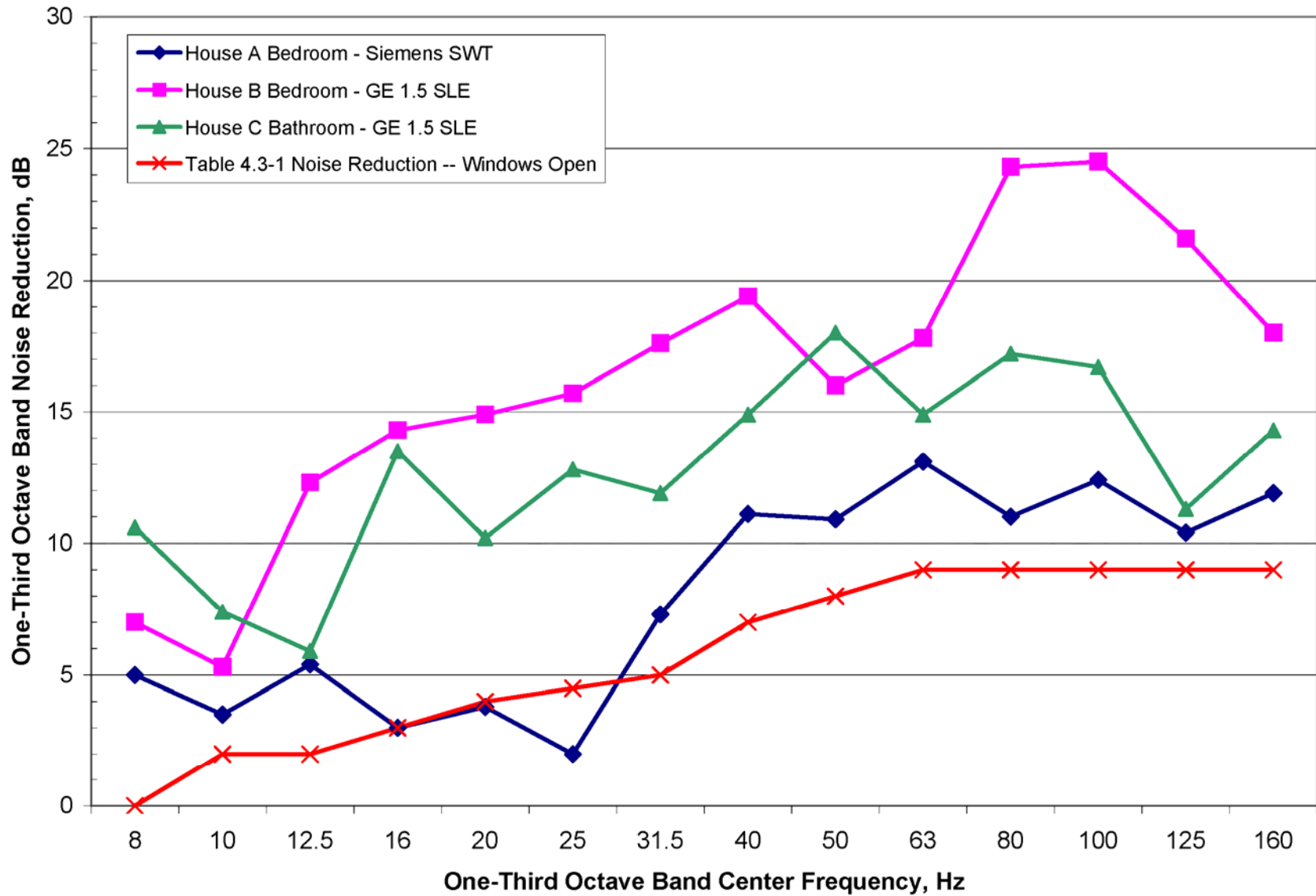




Figure 8.3-1b One-Third Octave Band Interior Noise Reduction – Windows Open



## 9.0 CONCLUSION

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Siemens SWT 2.93-93 and GE 1.5sle wind turbines at maximum noise at a distance more than 1000 feet from the nearest residence do not pose a low frequency noise or infrasound problem. At this distance the wind farms:

- ◆ meet ANSI/ASA S12.2 indoor levels for low frequency sound for bedrooms, classrooms and hospitals;
- ◆ meet ANSI/ASA S12.2 indoor levels for moderately perceptible vibrations in light-weight walls and ceilings;
- ◆ meet ANSI S12.9 Part 4 thresholds for annoyance and beginning of rattles;
- ◆ meet UK DEFRA disturbance based guidelines;
- ◆ have no audible infrasound to the most sensitive listeners;
- ◆ might have slightly audible low frequency noise at frequencies at 50 Hz and above depending on other sources of low frequency noises in homes, such as refrigerators or external traffic or airplanes; and
- ◆ meet ANSI S2.71 recommendations for perceptible vibration in residences during night time hours.

In accordance with the above findings, and in conjunction with our extensive literature search of scientific papers and reports, there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 1000 feet from the wind turbine types measured by Epsilon: GE 1.5sle and Siemens SWT 2.3-93.

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**HEALTH & FAMILY SERVICES**  
PUBLIC HEALTH SERVICES  
TELEPHONE (519) 352-7270 • FAX (519) 352-2166

June 1, 2009

His Worship Mayor Randy Hope and Councillors  
The Municipality of Chatham-Kent  
315 King Street West  
Chatham, ON N7M 5K8

Dear Mayor and Councillors:

**RE: REQUEST FOR FURTHER CLARIFICATION ON HEALTH EFFECTS OF WIND TURBINES**

I am aware that Council has received a great deal of conflicting information on this issue, including health complaints in our own Municipality alleged to be caused by proximity to wind turbines. I will explain the position of the Health Unit that there is currently no substantial basis to conclude that wind turbines are directly eroding the health of people.

Evidence for medical conclusions is categorized into three levels, with level I providing the strongest evidence and level III the weakest.

- Level I: Evidence obtained from at least one properly designed randomized controlled trial.
- Level II-1: Evidence obtained from well-designed controlled trials without randomization.
- Level II-2: Evidence obtained from well-designed cohort or case-control analytic studies, preferably from more than one center or research group.
- Level II-3: Evidence obtained from multiple time series with or without the intervention. Dramatic results in uncontrolled trials might also be regarded as this type of evidence.
- Level III: Opinions of respected authorities, based on clinical experience, descriptive studies, or reports of expert committees.

Unfortunately, statistical analysis is limited with regard to wind turbine effects because of the paucity of level I and II evidence. Most of the so-called studies purporting to document adverse health effects caused by wind turbines are self-reported accounts or

open surveys of health issues that are nonspecific and common irrespective of wind turbine exposure, such as insomnia, hypertension, anxiety, digestive disturbances and subjective sensory changes. These accounts have been reported by the media and have created an impression in the public before a rigorous analysis has confirmed that there is either excess morbidity or an association with wind turbines. Uncontrolled self-reporting eliminates any chance of scientific analysis as there is no motivation or reason to report a lack of symptoms or a way to include all people in proximity to turbines. There is no mechanism to exclude people from participating in a self-reported survey multiple times. The boundaries of proximity are often not even defined. The lack of controls (a sample of people not exposed to wind turbines), failing to blind the surveyors (they should not know the exposure history before asking the questions) and not defining the study population result in what researchers call preselection bias. Similar surveys in the past have tended to distort and overestimate the prevalence of many things from “cancer clusters” to sexual practices (Kinsey’s infamous sex surveys). There is no local data on the prevalence of these symptoms before wind turbines were installed, so it cannot be determined whether or not there has been an increase. The most eloquent spokesman for the anti-wind turbine activists, former UWO Dean of Medicine Dr Robert McMurtry, has admitted that there are no controlled studies, and he has called on the province to conduct such a study. This has been supported by at least one Ontario Health Unit, but this would be methodologically difficult. It is not possible to design a study to conclusively prove a lack of association, such as that wind turbines cannot cause health effects or that there are no ghosts.

At the present time we have people who have concluded, with gut-felt certainty, that they have health problems caused by wind turbines. These reports have received a great deal of media attention and organized political action groups have been formed which advocate for government action to address these health problems and suspend the construction of wind farms. These objectors operate web sites and write letters which promulgate dubious explanations such as infrasound induced DNA alterations, “wind turbine syndrome”, coined by anti-wind turbine activist Dr Nina Pierpont of Malone, New York for a complex of nonspecific symptoms and “vibro-acoustic disease”, tissue fibrosis first ascribed to extreme sound and vibration exposure in aviation environments by Portuguese investigators Alves Pereira and Castelo Branco, but later associated with the much lower sound levels of wind turbines and even automobiles. No other researchers have confirmed these findings. Wind turbine syndrome and vibro-acoustic disease impress lay persons as legitimate diseases which account for how they are feeling, but neither is listed in the International Classification of Diseases nor is described in any standard medical textbook. Most experts are skeptical that they exist.

So can we make sense of these complaints?

Most health complaints regarding wind turbines have centered on sound as the cause. Three kinds of sound are emitted by wind turbines: infrasound (oscillation frequencies less than approximately 10 Hz), low frequency sound of approximately 10-200 Hz and

the fluctuating aerodynamic “swish” from the turbine blades which is also low frequency, approximately 500-1000 Hz.

Infrasound from natural sources (meteors, volcanic eruptions, ocean waves and wind) surrounds us and is below the audible threshold. The infrasound emitted from wind turbines is at a level of 50 to 70 dB, also well below the audible threshold. There is a consensus among acoustic experts that the infrasound from wind turbines is of no consequence whatsoever. A problem is that objectors often use the term infrasound incorrectly when they are referring to low frequency sounds.

Low frequency sounds below 40 Hz cannot be distinguished from background noise due to the wind itself. Perceptible (meaning above the background noise) low frequency noise can be produced by wind turbines under conditions of unusually turbulent wind conditions, but the actual sound level depends on the distance of the listener from the turbine, as the sound attenuates (falls off). The higher the frequency and the higher the temperature, the greater the sound attenuates with distance. Terrain and humidity are other factors. The low frequency noise emitted by spinning wind turbines could possibly be annoying to some when winds are unusually turbulent, but there is no evidence that this level of noise could be harmful to health. If so, city dwelling would be impossible due to the similar levels of ambient noise levels normally present in urban environments. It is not usually the low frequency nonfluctuating noise component that provokes complaints.

The fluctuating aerodynamic sound (swish) in the 500-1000 Hz range is from the wind turbine blades disturbing the air, modulated by the blades passing the tower which changes the sound dispersion characteristics in an audible manner. This fluctuating aerodynamic noise is the cause of most noise complaints regarding wind turbines, as it is harder to become accustomed to fluctuating noise than to noise that does not fluctuate. The noise limits imposed by the Ministry of the Environment for wind turbines are designed to prevent noise issues but some wind turbines produce noise levels that may be irritating and even stressful to some people who are more sensitive to noise. Sleep disturbance can occur. Others exposed to the same noise levels may experience no difficulty. There is no evidence of direct effects to health by this level of noise but there could be indirect effects from annoyance-induced stress. One paper categorically states that the only health effect of wind turbine noise is annoyance.<sup>1</sup>

There is a large body of medical literature on stress and psychoacoustics. There is a great deal of individual variation in the response to any given stimulus and legislated limits to noise and other annoyance factors are not designed to prevent problems in the most sensitive members of the population. Three factors that seem particularly

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<sup>1</sup> Regan B., Casey T.G. Wind Turbine Noise Primer, Canadian Acoustics Special Issue, 34 (2) June 2006



pertinent to the discussion of wind turbine effects are the fear factor, also called the nocebo effect, and two medical conditions, sensory integration dysfunction and somatoform disorders.

The large volume of media coverage devoted to the alleged adverse health effects of wind turbines understandably creates an anticipatory fear in some that they will also experience adverse effects from wind turbines. Every person is suggestible to some degree. The resulting stress, fear and hypervigilance may exacerbate or even create problems which would not otherwise exist. In this way, anti-wind farm activists may be creating with their publicity some of the problems which they describe. This is the nocebo effect and it is the negative counterpart to the placebo effect where belief in an intervention may produce positive results.

Sensory integration dysfunction is a little-understood condition of abnormal sensitivity to any or all sensory stimuli (sound, touch, light, smell, taste). The afflicted experience unpleasant overpowering sensations to ambient conditions considered normal by most people. There is little data on the prevalence of this condition and it may be more common than is realized. Such individuals would be more sensitive to wind turbine noise than most.

Somatoform disorders are characterized by physical symptoms which reflect psychological states rather than physical causes. Conversion is the unconscious expression of stress and anxiety as a physical symptom and it is very common. Common conversion symptoms are vague sensations of tingling or discomfort, fatigue, poorly localized abdominal pain, headaches, back or neck pain, weakness, loss of balance, hearing and visual abnormalities. The wind turbine controversy has raised the rhetoric to stressful levels, and the similarities of human stress responses and conversion symptoms to those described as so-called wind turbine syndrome are striking.

In summary, there is no scientifically valid evidence that wind turbines are causing direct health effects, although the body of valid evidence is limited. It is unlikely that evidence of adverse health effects will emerge in the future because there is no biologically plausible mechanism known by which wind turbines could cause health effects. There are wind turbines in urban environments, including Toronto, that have not been causing problems. The European experience would indicate that wind farms can be compatible with rural environments. An annoyance factor undoubtedly exists to which there is individual variability. Associated stress from annoyance, exacerbated by all the negative publicity, is the likely cause for the purported erosion of health that some people living near rural wind turbines are reporting. Stress has multiple causes and is additive.

Unfortunately, there has been some misunderstanding regarding the role of the Medical Officer of Health and the Health Unit in these matters. It is beyond the scope of the

Chatham-Kent Health Unit to address this in any but a general manner. In my opinion the issue of wind turbine noise and associated stress needs to be managed at the Provincial level. If the Ministry of the Environment noise guidelines for wind turbine installations are exceeded, affected people have the option to pursue compensation, but the Chatham-Kent Board of Health has confirmed that it is not the role of the Health Unit to become involved in private litigation matters. From the outset, when requested by Council, the Health Unit and I have attempted to provide a balanced, evidence-based and scientifically valid appraisal of this whole situation to Council. As a result, anti-wind farm activists have attacked me personally on internet sites, accused me of being financially influenced by wind turbine manufacturers (untrue) and even made complaints about my conduct to regulatory bodies. Letters to the Chatham Daily News have castigated me for neglecting the health of Chatham-Kent citizens with the kind of inflammatory phrases spoken, it seems to me, in the language of people with a higher regard for their own convictions than for the facts.

Sincerely,

W. David Colby, MSc, MD, FRCPC  
Acting Medical Officer of Health  
Chatham-Kent Health Unit

Encl.:

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# ***ACOUSTIC CONSULTING REPORT***

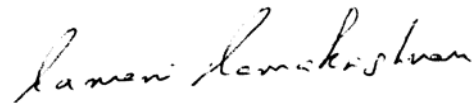
***Prepared for the Ontario Ministry of the Environment***

## **WIND TURBINE FACILITIES NOISE ISSUES**

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**Aiolos Report Number: 4071/2180/AR155Rev3  
DECEMBER 2007**

Author            Ramani Ramakrishnan, Ph. D., P. Eng.  
                      Lead Acoustician



Signature

Date: 28 December 2007

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## **EXECUTIVE SUMMARY**

All proponents of a wind farm development need to apply for a Certificate of Approval from the Ministry of the Environment of Ontario. The noise assessment report required for the approval process uses the guideline Ministry document, “Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators” released in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits.

The Ministry has now initiated a review of the interpretation of the above policies, due to expanding body of knowledge of the noise impacts of wind turbines. The main aim of the proposed review is to assess the appropriateness of the Ministry’s approach to regulating noise impacts of wind turbines.

The scope and requirements of the review can be summarized as: a) Review of the 2006 doctoral dissertation by van den Berg; b) Review of available noise policies and guidelines; review of relevant scientific literature; and review of MOE’s current noise policies as applied to wind turbine noise and c) Provide expert opinion based on the above findings; and d) Prepare a report that provides advice on the state of the science regarding wind turbine noise, and on MOE policies and procedures that relate to wind turbine facilities. The results of the investigations are described below.

Van den Berg’s research was initiated as a result of complaints, in Netherlands, against an existing wind farm in Germany very close to the Dutch border. The main hypotheses of the research are: a) atmospheric stability, particularly stable and very stable conditions happen mostly at night time and the hub-height wind speeds can be higher than those predicted from the 10 m high wind speeds using standard methods, such as the logarithmic profiles of the IEC standard. And hence, the wind turbine noise levels can be higher than expected. It was also conjectured that these discrepancies are prevalent during summer months; and b) beat-sounds



can become very pronounced during stable and very stable conditions. Although, the data of van den Berg's research did not provide conclusive scientific evidence to support the above hypotheses, further review of the literature showed that some of the basic conjectures may well be true. Hence, the research of van den Berg must be considered as the catalyst that started serious discussion on many noise aspects of wind farm. Future research must therefore provide strong scientific data to validate these different noise concerns.

The noise policies from different Canadian provinces, USA states and a few other countries were reviewed. General comparison of the noise regulations was presented. The main differences between the different regulations seem to be: i) in the acceptable noise limits; and ii) in the evaluation of receptor noise levels from the cumulative operation of the turbines in the wind farm. Further, some jurisdictions have special legislation concerning wind turbines, while others apply general recommendations. The Ministry of the Environment assessment process in Ontario is similar to other jurisdictions.

A literature review, focussed mainly on a) Metrological effects on wind turbine noise generation; b) Assessment procedures of wind turbine noise levels and their impact; c) Particular characteristics of wind farm noise; and d) Human responses to wind farm noise levels, was conducted. It showed that - local terrain conditions can influence meteorological conditions and can affect the expected noise output of the wind turbines; assessment procedures of sound power levels and propagation models, applied in different jurisdictions are quite similar in their scope; wind farm noise do not have significant low-frequency (infrasound) components; and modulations effects can impact annoyance;

The Ministry of the Environment's procedures to assess wind farm noise levels follow a simple procedure that is sound for most situations. However, additional concerns still need to be addressed in the next round of revisions to their assessment process. These revisions may need to be addressed after the results from future research provide scientifically consistent data for effects such as meteorology, human response and turbine noise source character.

## 1.0 INTRODUCTION

### 1.1 BACKGROUND

The Ministry of the Environment released a guideline document, “Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators” in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits. The revisions to NPC-205/NPC-232 (in draft form) did not change the evaluation of noise limits and/or procedures applicable to wind turbines. The three Ministry documents are enclosed in Appendices A through C.

The Ministry has now decided to initiate a review of the interpretation of the above policies, due to expanding body of knowledge of the noise impacts of wind turbines. The main aim of the proposed review is to assess the appropriateness of the Ministry’s approach to regulating noise impacts of wind turbines. And the Ministry, to support the proposed review, has retained Aiolos Engineering to provide acoustical technical expert advice on the recent findings about low frequency and wind profiles on wind turbine noise impacts.

The scope and requirements of the technical advice can be summarized as shown below:

- (1) *Review of the 2006 doctoral dissertation by van den Berg;*
- (2) *Review of*
  - 2.1 *available noise policies and guidelines;*
  - 2.2 *Review of relevant scientific literature; and*
  - 2.3 *Review of MOE’s current noise policies as applied to wind turbine and*
- (3) *Provide expert opinion based on the above findings;*
- (4) *Participate in a focus group discussion; and*
- (5) *Prepare a report that provides advice on the state of the science regarding wind turbine noise and on MOE policies and procedures that relate to wind turbine facilities.*

---

## **2.0 REVIEW OF G. P. VAN DEN BERG'S DISSERTATION**

### **2.1 BACKGROUND**

Dr. G. P. van den Berg of the University of Groningen conducted research on the noise characteristics of wind turbines, the impact of wind profiles on its propagation as well as the subjective response of sensitive receptors. The results of the above research are summarized in the 2004 Journal of Sound and Vibration article (Reference 2) with the details given in his 2006 doctoral dissertation (Reference 1).

A list of documents used for this assessment is enclosed in the reference list. *NOTE:* References 2, 3 and 4 by van den Berg presents only summary results of his research and the complete details are included in his dissertation (Reference 1). Hence, references 2, 3 and 4 will not be commented upon in this review.

The main aims of van den Berg's dissertation can be summarized as follows:

- i) A group of residents complained against the perceived noise effects from a wind farm located along the border between Germany and Netherlands and were unable to obtain satisfactory resolution from the authorities and hence the university's Science Shop for Physics was retained to investigate the validity of the residents' claims;
- ii) The main complaints seem to centre around perception during evening and night hours, and hence the dissertation focussed on atmospheric stability and the resulting noise effects;
- iii) The main hypotheses are: a) atmospheric stability, particularly stable and very stable conditions happen mostly at night time and the hub-height wind speeds can be higher than those predicted from the 10 m high wind speeds using standard methods, such as the logarithmic profiles of the IEC standard. And hence, the wind turbine noise levels can be higher than expected. It was also conjectured that these discrepancies are prevalent during summer months; and b) beat-sounds can become very pronounced during stable and very stable conditions.

The research uses a set of measurements near one wind farm as well as wind data from locations between 10 km and 40 km from the wind farm area. The whole thrust of the dissertation is to prove the hypotheses listed above.

The dissertation is broken into ten chapters, four general sections and four appendices. The chapter titles are: I) Wind power, society and this book: an introduction; II) Acoustical practice and sound research; III) Basic Facts; IV) Loud sound in weak winds; V) The beat is getting stronger; VI) Strong winds blow upon all turbines; VII) Thinking of solutions; VIII) Rumbling sound; IX) General conclusions and X) Epilogue.

Chapter I is basically an introduction and a justification for conducting the doctoral research by van den Berg. The reasons are seen to be based on anecdotal responses rather than from a truly scientific and statistical analysis of response surveys. Chapter II is a strong criticism of acoustic consultants and their inadequate effort in finding the true wind turbine noise levels and their potential impacts.

Chapters III, IV, V and VI are the relevant chapters for this review and assessment. The assessment will be presented in subsequent sections. Chapters VII through X are not critical for the current assessment and will not be commented upon. The assessments are presented next.

## **2.2 CHAPTER III – BASIC FACTS**

Chapter 3 contains four sections and Sections 2 and 4 provide relevant background materials. Section 2 discusses wind profiles and Section 4 presents the many sources of wind turbine sound.

### ***2.2.1 Wind Profiles and Atmospheric Stability***

The main contention of this dissertation is that the hub-height velocity can be much higher than predicted with simple formula used currently in standards and other literature. This section presents two simple velocity profile equations to obtain wind velocities at different heights (Equations III.1 and III.3). Eq. III.3 is the standard logarithmic profile used in current literature.

This equation is being questioned as to its validity by this dissertation. Equation III.1 is a simple power law relationship with a shear coefficient as the exponent. Even though the dissertation states that Eq. III.1 has no physical basis, the dissertation applies this equation with ‘suitably chosen’ shear coefficient ‘m’ throughout the dissertation. Equation III.1 has been applied in many areas of engineering application and it is based both on dimensional analysis and empirical relationship obtained from field measurements. These two equations from Reference 1 are presented here for completeness sake.

$$V_{h2} / V_{h1} = (h_2/h_1)^m \quad \text{III.1}$$

where ‘m’ is the shear coefficient,  $h_1$  and  $h_2$  are the two heights and V are the wind velocities at heights  $h_1$  and  $h_2$ .

$$V_{h2 \log} / V_{h1} = \log(h_2/z_0) / \log(h_1/z_0) \quad \text{III.3}$$

where  $z_0$  is a roughness length of the surrounding terrain.

### ***2.2.2 Main Sources of Wind Turbine Sound***

A brief summary is presented of the different mechanism of noise generation including the interaction between the mast and the blade. Considerable amount of literature is available that outlines the noise from rotating aerofoil from early 1900s onwards. Hence, the information presented is a summary of earlier research.

However, it must be pointed that the dissertation mentions and/or presents information throughout the dissertation either heuristically or by presenting only scant data. One such case can be seen in Chapter III where it is stated, “An overview of stability classes with the appropriate value of m is given in Table III.1.” No documentary evidence is given for the chosen values of ‘m’ or how the appropriateness of ‘m’ was determined. The reason this point is made here is the ‘stability class’ designation can change drastically depending on the value of ‘m’. Table III.1 of Reference 1 is reproduced below.

**Table III.1: stability classes and shear exponent  $m$**

Pasquill class	name	comparable stability class [TA-Luft 1986]	$m$
A	very unstable	V	0.09
B	moderately unstable	IV	0.20
C	neutral	IV2	0.22
D	slightly stable	IV1	0.28
E	moderately stable	II	0.37
F	(very) stable	I	0.41

### **2.3 CHAPTER IV: LOUD SOUNDS IN WEAK WINDS – EFFECT OF THE WIND-PROFILE ON TURBINE SOUND LEVEL**

This is one of the most important chapters in the dissertation. The main hypothesis of the chapter is to show that the hub-height velocity can be higher than predicted from the 10 m high wind speeds using standard methods during stable and very stable atmospheric conditions and hence the wind turbine noise levels can be higher than expected even though the ground level velocities can be small at 2 m and 10 m heights. Such a wind-profile is possible when the atmospheric stability class is a combination of Pasquill Classes E and F with quiet winds and no cloud cover.

Chapter IV is supposed to prove the above hypothesis with scientific support.

#### **2.3.1 Basic Assessment**

The first three sections of the chapter provide background information on the Rhede wind farm in northwest Germany that abuts Netherlands. Even though, the noise assessment showed that the wind farm complies with both German and Dutch guidelines, nearby Dutch residents complained about the noise levels. The Science Shop for Physics of the University of Groningen (van den Berg's faculty) was retained to assist the residents to resolve their concerns. Section 3 presents anecdotal responses of two residents and their perception of wind turbine noise – 'pile driving sound', 'thumping sound', 'endless train sound' and such. There is no subjective polling under a blind survey to accompany the technical data presented.

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### ***2.3.2 Sound Emission and Sound Immission Levels***

Long-term noise measurements were conducted at two receptor locations near the Rhede Wind Farm at two different time periods. Location A is 400 m west of the wind farm and Location B is 1500 m west of the wind farm. Wind velocities at 2 m and 10 m heights were measured only at Location A. ***NOTE: It must be pointed out that wind speeds at hub-height were not measured.*** The area around Location B has both low and tall trees in its vicinity. The following explanation and we quote, “As, because of the trees, the correct (potential) wind velocity and direction could not be measured on location B, wind measurements data provided by the KNMI were used from their Nieuw Beerta site 10 km to the north. These data fitted well with the measurements on location A” was offered to justify the use of data from a far-off wind-measuring location. The above statement is heuristic at best since no data (figures and/or tables) were provided to back the above claim. Hence, it was very difficult to make sense of the data presented in the dissertation document. Similarly, meteorological data from Elde site (40 km to the west) was used to establish neutral and stable atmospheric classes for the above two sites. Even though the section states that not all Elde observations would be valid for Locations A and B, the report still used the Elde information without qualifying its validity.

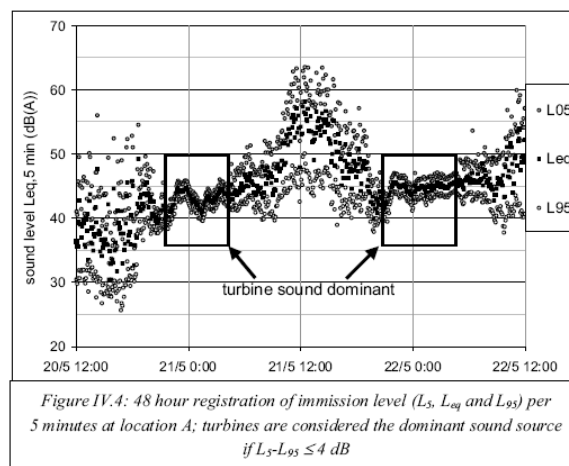
The main aim of the fourth chapter was to show that the atmospheric class during night is ‘stable’ or ‘very stable’. The stable classes, supposedly, produce hub-height wind speeds that are higher than day time values, even though the 10 m high wind speeds could be low at night and the standard wind profiles are not able to predict the high hub-wind speeds at night. The outcome of the above hypothesis is that the night time noise levels, therefore, are higher than expected. However, as shown above, the establishment of atmospheric classes itself becomes suspect. Hence, the subjective perception that the noise levels were high may be due to low ambient sound levels during the late evening and night time hours, thereby making the wind farm noise audible.

### 2.3.2.1 Sound Emission Levels

Sound emission levels are the sound levels generated by the wind turbines and it is crucial to extract the levels from field measurements of overall levels. The noise levels from nine turbines were measured (Section 6) and an empirical relationship between the sound power and turbine rpm was established. The resulting sound power levels were used to calculate the noise levels at receiver locations and compare them with local measurements.

### 2.3.2.2 Sound Immission Levels

Sound immission, a phrase used in Europe, refers to the sound levels at receptor locations. Sound immission levels at Locations A and B were discussed in Section 7 of Chapter IV of Reference 1. The data provided is very difficult to analyse and at times very confusing. 371 hours of data for Location A and 1064 hours of data for Location B were collected. Since the monitors were un-manned, the differences in A-weighted sound levels between the 5<sup>th</sup> and 95<sup>th</sup> percentiles over 5-minute intervals were used to determine the dominance of turbine sound. The report uses a value,  $L_5 - L_{95} \leq 4$  dBA, to deduce (Figure IV.4 of Reference 1) the duration of high sound levels at night time and at day time. There was no reason given as to the selection of the 4 dBA number. One would have expected a lower value, if the wind turbines were the main dominant noise sources. Actually, the value was close to 3 dB as described in Chapter V of Reference 1 (page 71 –  $R_{bb,90}$  at Location P was around 3 dB). Figure IV.4 is reproduced below.



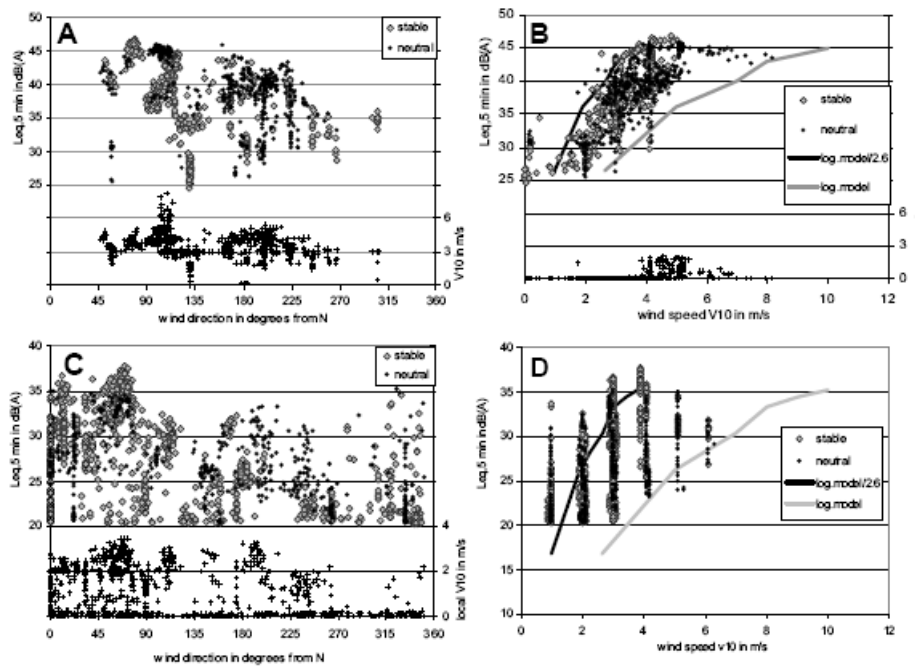


The criterion of  $L_5 - L_{95} \leq 4$  dBA to determine the dominance of wind turbine noise is critical to the assessment. If the sound was steady during the 5-minute period, the above difference would be zero. Since outdoor sound levels are never steady, one would expect some variability. However, it is our belief that 4 dBA range is too high. If one were to reduce the difference to 2 dBA or 3 dBA, the night time duration for dominant sound levels would reduce substantially compared to the results presented in Table IV.3 of Reference 1. Table IV.3 is reproduced below.

**Table IV.3: total measurement time in hours and selected time with dominant wind turbine sound**

Location	total time (hours and % of total measurement time at location)	Night	Evening	Day
		23:00-6:00	19:00-23:00	6:00-19:00
A: total	371 h	105	75	191
A: selected	92 h 25%	76 72%	9 12%	7 4%
B: total	1064 h	312	183	569
B: selected	136 h 13%	119 38%	13 7%	4 0,7%

The sound immission levels from all the measurements (the entire 1435 hours of data) were organized into the dominant turbine noise levels based on the 4 dBA difference and presented in Figure IV.5 of Reference 1, which is reproduced below. This figure with four sub-plots, is the most difficult figure to decipher. This is one of the most important figures used to conclusively provide evidence for the main argument of the dissertation. If one does not accept the 4dBA argument, the whole data structure of Figure IV.5 of Reference 1 is suspect. Further to cloud the issue, stable and neutral atmospheric classes, gleaned from Elde data (located 40 kms away) was superimposed. [Reference 1 on Page 47 does state that not all Elde data would be valid for Locations A and B, but continues, anyway, to use the invalid data to determine stability classes]. One must also infer that ‘stable’ classes occur only at night time and ‘neutral’ classes occur during the day time, even though the above was not stated explicitly in the report. No proper explanation was given for applying the above inference.



*Figure IV. 5: measured sound levels  $L_{eq,5 min}$  at locations A (above) and B (below) as a function of median wind direction (left) and average wind speed (right) at reference height (10 m), separated in classes where the atmosphere at Eelde was observed as stable (open diamonds) or neutral (black dots). Also plotted are expected sound levels according to logarithmic wind profile and wind speed at reference height (grey lines in B and D), and at a 2.6 times higher wind speed (black lines in B and D). Figures A, B and C also contain the wind speed  $v_{10}(A)$ ,  $v_2$  (B), and the local  $v_{10}$  (C) disturbed by trees, respectively.*

Figures IV.5 B and IV.5D Reference 1 present the variation of ‘dominant’ turbine noise levels as a function of wind speed measured at a height of 10 m. **NOTE:** It must be pointed out that no wind speeds were measured for Location B. The data points ( $L_{eq, 5 min}$  in dBA) were also separated into ‘stable’ and ‘neutral’ atmospheric classes. In addition, the calculated sound levels from the sound power data from Section IV.6 were also plotted in these two figures. The wind speed at 10 m height for the calculated plot was evaluated using the logarithmic wind profile of Equation III.3 shown in Section 3 of the current assessment report. Since the logarithmic wind profile was supposed to be incorrect, a corrected noise level plot, by applying a factor of 2.6, was also included in Figures IV.5B and IV.5D of Reference 1. These two figures were used to make two strong statements against the procedures used to assess wind-turbine and wind farm noise impacts.

Statement I: ‘Stable’ atmospheric conditions occur at night time and wind turbine noise levels are higher than expected due to high wind-velocities at hub-height.

Statement II: Logarithmic wind profile, generally used in standard procedures, is incapable of predicting current wind speeds at various heights for ‘Stable’ atmospheric classes, occurring at night time. And hence, these higher than expected noise levels occur at night time with low ground wind speeds, thereby, increasing the impact on residents.

However, the two figures do not provide conclusive evidence to support the above two statements for the following reasons. Contrary evidence to Statement I will be further discussed in the next section with field data from New Zealand and Australia.

- a) The ‘stable’ and ‘neutral’ class designations used in the two figures are applied from a location 40 kms away and hence not valid for Locations A and B;
- b) Both classes seem to produce high as well as low sound levels as clearly seen for Location B (Figure IV.5D Reference 1);
- c) The light grey sound level line supposed to represent the ‘neutral’ class quite accurately (as stated in Chapter III of the dissertation). If that were to be true, all of the ‘neutral’ class data points would have collapsed near that line. However, that was not the case, as the data points are scattered all over the figures;
- d) Even at a distance of 400 m from the wind farm (Location A), only a small percentage of the ‘neutral’ class noise levels is near the neutral line;
- e) Finally, if the  $L_5 - L_{95}$  value is close to 2 or 3 dBA, the entire dominant sound levels at night time could occur well below the 25% to 35% time presented in this dissertation.

As part of the current investigation Aiolos Engineering undertook a brief review of summer weather data near a wind farm located adjacent to Lake Huron in Southern Ontario. Summer data was reviewed as the main hypothesis of van den Berg is that the wind speed discrepancies due to stability classes are severe during the evening and night hours of summer months. The

objective of this review was to test the rigour of the two “van den Berg” Statements I and II. Since this review was conducted in the context of the current investigation and this report, the scope of the review was limited both in its duration and site selection. The review of this data will show that limited data of the type that van den Berg relied on cannot be used to draw strong conclusions.

Aiolos Engineering compiled wind speed data from one weather station in Ontario for a period of three summer months (June, July and August 2006). The Environment Canada’s weather station at Goderich, Ontario is situated within a few kms of a wind farm with 21 wind turbines. The Kingsbridge wind farm has the capacity to generate 40 MW of power. The data for the three month period was compiled in different formats and the results are presented in Appendix D. The atmospheric stability classes were approximated using the information from the AIR-EIA website (Reference 19). Even a cursory perusal of the Appendix D data would show that the correlation between stability classes and power generation is quite inconsistent. The power generated by the wind farm was obtained from the Independent Electricity System Operator’s data base for Ontario (Reference 34). Unless a detailed study of the wind power generation and wind speed behaviour at the wind farm location is conducted, one cannot make strong conclusions as presented by van den Berg’s work. Another salient observation from Appendix D data is that the wind farm power generation and wind speed behaviour is highly localised, controlled by the local conditions

One must point out at this juncture, that the conjectures presented in van den Berg’s Statements I and II may well be true. However, the research presented in van den Berg’s dissertation has not provided strong scientific evidence for the same. In addition, the data of figures IV.5 clearly shows that the sound levels at Location A, 400 m west of the wind farm is less than 40 dBA and the noise levels at Location B, 1500 m west of the wind farm, is less than 35 dBA for a substantial portion of the measurement period.

## **2.4 CHAPTER V: THE BEAT IS GETTING STRONGER – LOW FREQUENCY MODULATED WIND TURBINE SOUND.**

Chapter V deals with the effect of frequency modulation of the wind turbine noise levels. This chapter is an important chapter since it is supposed to provide evidence that the beating phenomena gets stronger with worst results during the ‘stable’ atmospheric classes. The ‘stable’ atmospheric classes are supposed to occur only during late evening and night time hours and the turbine is supposed to generate higher than expected noise levels with the ambient sound levels at the receivers being low due to lower than expected ground speeds. The inference here, therefore, is that any modulation of higher noise levels would cause additional hardships on the receiver. This chapter aims to show that the above is true.

Chapter V is broken into 3 main sections. Section V.1 discusses the effects of atmospheric stability on wind turbine noise generation. It discusses, three possible effects, purely as theoretical conjunctures that beating (or modulation) can be due to - a) the increase in the angle of attack changes between the blade at its highest location and at its lowest location during stable conditions; or b) increase in the wind direction gradient between the blade at its highest location and at its lowest location during stable conditions; or c) reduced wind turbulence during stable conditions. No supporting experimental evidence was forthcoming. We agree that purely from theoretical consideration that the three possible mechanisms can produce amplitude modulation phenomena. But, does this happen only for ‘stable’ and ‘very stable’ atmospheric conditions and only at night time?

The other major misconception arising out of this chapter is the terms used to describe the said phenomenon – ‘swishing’, ‘thumping’, and ‘beating’. The beating phenomenon in acoustics called *beat* is a special event when two sounds occur with their dominant frequencies very close to each other. A general description of *beating* is presented in Appendix E. The amplitude modulation phenomenon is different from *beating*. The acoustical principles that describe the amplitude modulation phenomenon are generally considered to be related to the movement of the turbine blades through air and the interaction of the blades with the stationary mast. In addition, the amplitude modulation could be caused by the nature of wind itself – random both in speed

and direction. Irrespective of the underlying principles, the amplitude modulation produced by wind turbines is a different phenomenon from acoustical *beating*.

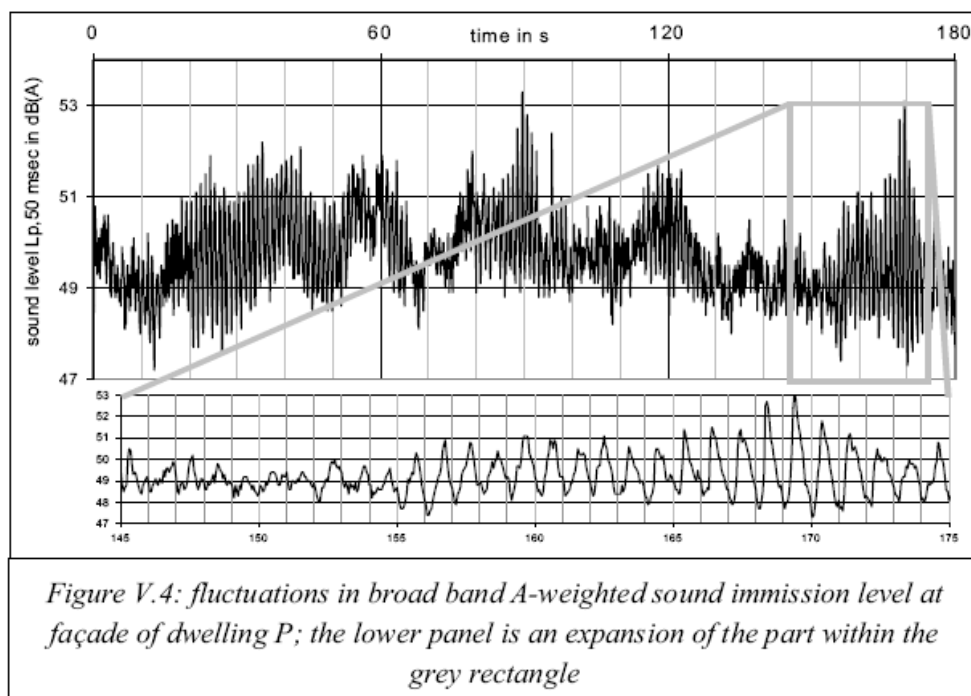
The UK working group on Wind Farm noise (Reference 30) studied the phenomenon of amplitude modulation and found the levels inside residential bedrooms to be below the sleep disturbance level. Importantly, the UK report recommended that further studies be conducted to understand the amplitude modulation better. [Further descriptions of the aerodynamic modulation will be presented in Section 4].

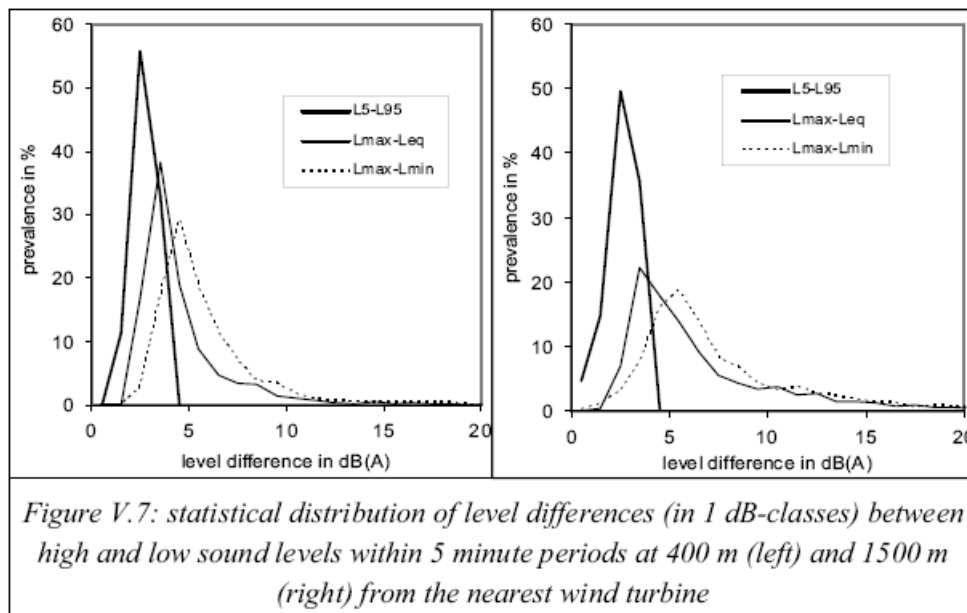
Section V.2 presents measurement at three locations; two near the Rhede wind farm and the third location (Location Z) is near a single small wind turbine. Between 10 and 15 minutes of data were collected. The measurement results are presented in terms of spectral variations. The wind velocity was measured only near one location and the wind speed data for Location Z was obtained from a number of nearby weather stations. Two conclusions were obvious from the results:

- a) the infra-sound, when measured as dBG with the G-weighting scale, was found to be not audible, approximately between 15 – 20 dB below the threshold of perception, indicating that modern wind farms do not generate infrasound levels that are perceptible. For information on G-weighting network, please see Reference 31;
- b) the A-weighted sound levels correlated with spectra around 400 Hz which indicates the major source is the trailing edge noise.

The main thrust of this chapter was to discuss the amplitude modulation phenomena. The modulation at Location P was audible during the measurements period, but very small at Locations R and Z. The main effect of the modulation is not to produce low frequency sounds, but change the amplitudes which are discernable by the receivers. The results showed amplitude modulation at Location P with a variation of about 5 dBA between maximum and minimum. Even though the measurements were conducted for a long duration, only 180 second of measured data was shown to prove the existence of the modulation (beating) in Figure V.4 of

Reference 1. The modulation was seen to be strong only for 30 seconds. Even though the variation was 1 dB more at Location R, no modulation was discernable. No explanation was given for these discrepancies. Even though the level variation did not indicate beating at Location R, the level variations for Locations A and B from Chapter IV were shown in Figure V.7 of Reference 1 to conjecture that modulation would happen at these locations, 28% of the time and 18% of the time respectively. Since the measurements at Locations R, P and Z were conducted at early morning hours (midnight), it was assumed to be stable weather conditions. No data was provided to substantiate the absence of modulation during other weather conditions, such as 'neutral' and/or 'unstable' atmospheric classes. Hence, one cannot immediately conclude that modulation occurs only during the 'stable' and 'very stable' atmospheric class. Figures V.4 and V.7 of Reference 1 are reproduced below,





Finally, Section V.3 discusses the perception of the modulated sound. It begins by quoting the subjective response work of Pedersen and Waye (Reference 5) that about 20% of residents would be annoyed with noise levels in the range of 37.5 dBA to 40 dBA. It then jumps to anecdotal responses of two residents near the Rhede farm. There are no studies cited in van den Berg's work that show a correlation between modulated sound and annoyance and hence van den Berg conjectures the annoyance would be worse since the expected amplitude variations make the perception of the sound strong. However, no evidence other than anecdotal responses was forthcoming.

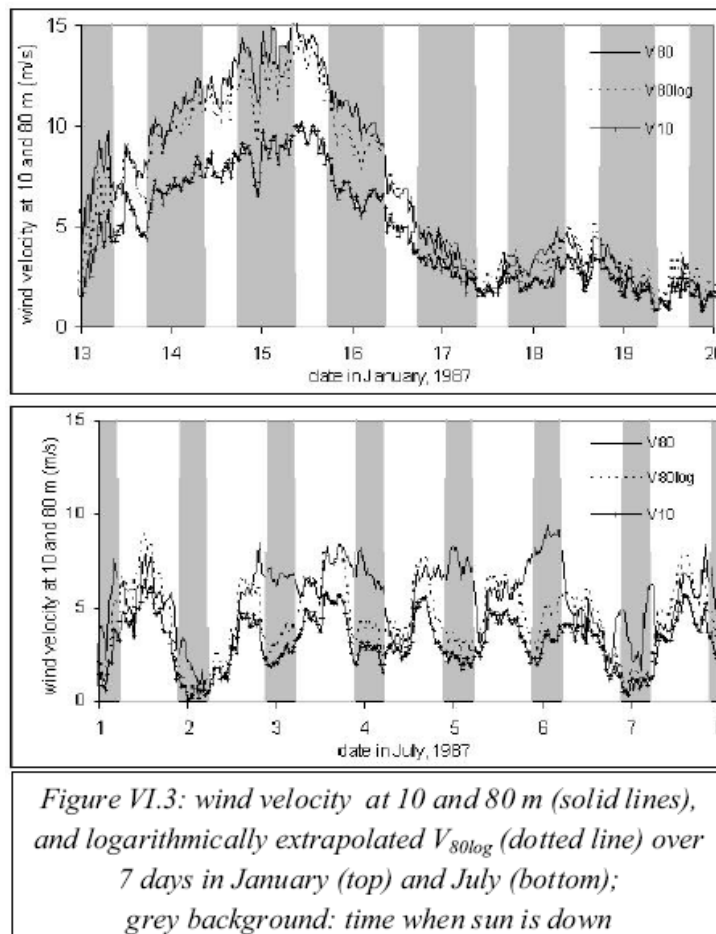
## **2.5 CHAPTER VI: STRONG WINDS BLOW UPON TALL TURBINES – WIND STATISTICS BELOW 200 M ALTITUDE**

This chapter deals with actual wind speed data from one site in western part of the Netherlands. The wind velocities at different heights, 10 m, 20 m, 40 m, 80 m, 140 m and 200 m were measured at half-hour intervals. The results, averaged for the entire year showed that higher wind velocities compared to the predicted wind speeds from the 10 m high wind velocity, indicating a stable atmosphere. Even the daily variations over seven days in summer months are small during the night time hours (Figure VI.3 of Reference 1, reproduced below).



The data described in Section 2.3.2.2 and presented in Appendix D was further analysed to look at the daily variations in wind speeds. In addition to Goderich weather station, the data from a few more weather stations located within 30 km radius of existing wind farms were compiled by Aiolos Engineering. Figures 2.1 thru' 2.6 show results of one-hour averaged wind speeds from three weather stations near three wind farm sites in southern Ontario. The weather data was collected at a height of 10 m above ground. The daily variations for a few summer days shown in Figures 2.1, through 2.6 seen to indicate substantial variations in wind speeds from day to day. As was explained in Section 2.3, summer data was reviewed as the main hypothesis of van den Berg is that the wind speed discrepancies due to stability classes are severe during the evening and night hours of summer months.

The measurement results of Botha [Reference 22] for four sites in New Zealand and Australia showed contradictory results of wind speed gradient. They will be discussed in Section 4. Hence, the main conclusion here is that the data presented in Chapter VI of Reference 1 is valid only for that one site in Netherlands.



The chapter then calculates expected power production at these velocities as well as calculates noise levels from the wind farm. The results show that the discrepancy for the Cabauw site between stable noise and standard logarithmic wind profiles is of the order of 2 dB. These differences are averaged from one site. The main drawback of the results of this chapter is that they are not transferable to every wind farm site in the world.

One must point out that it may be possible that during summer months stable and very stable conditions may exist at night time producing higher than expected noise levels and hence increasing the impact. However, the data presented so far does not lead one directly to that conjecture.

Figure 2.1 Elora Wind speeds

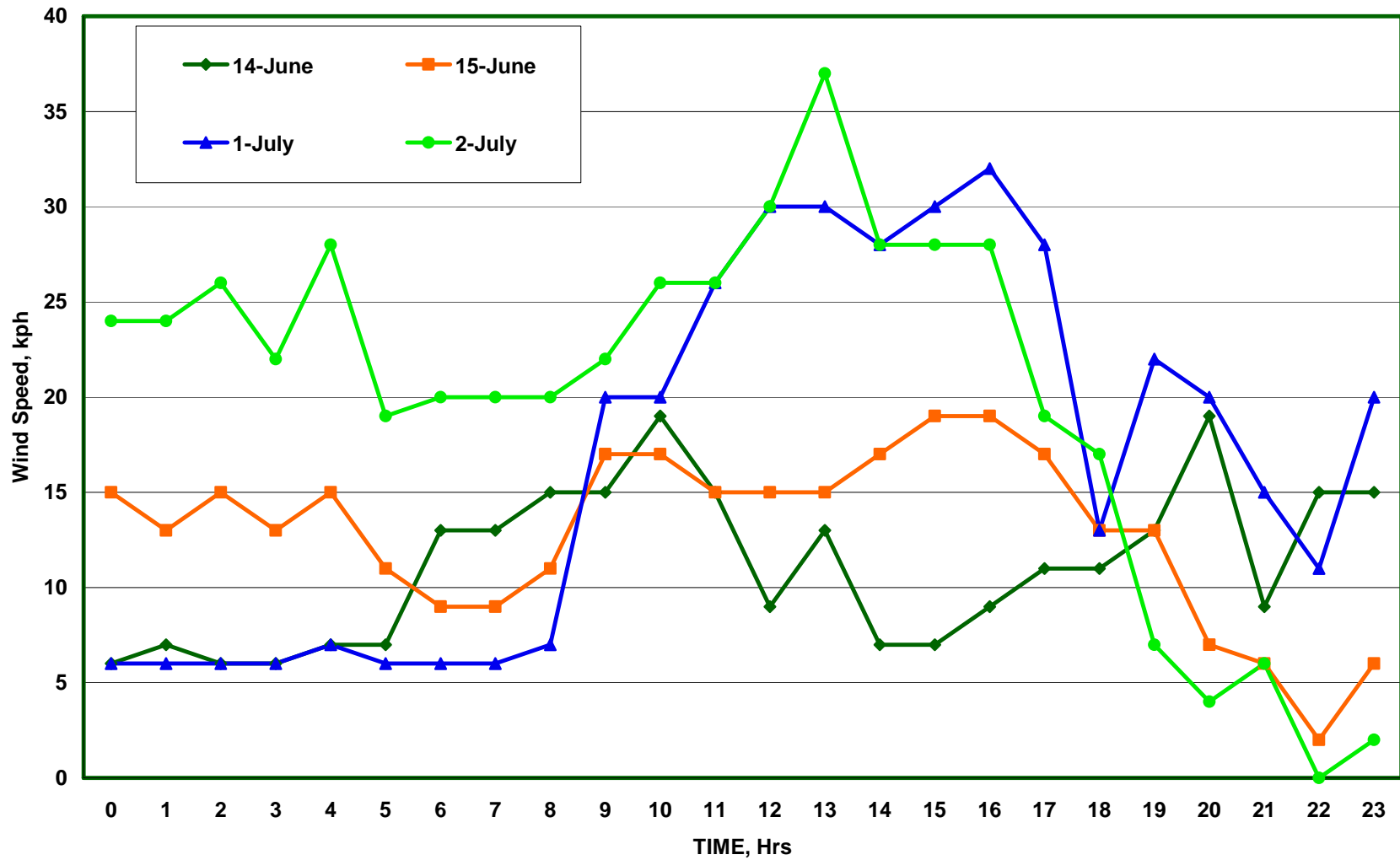


Figure 2.2 Elora Wind speeds - 2.

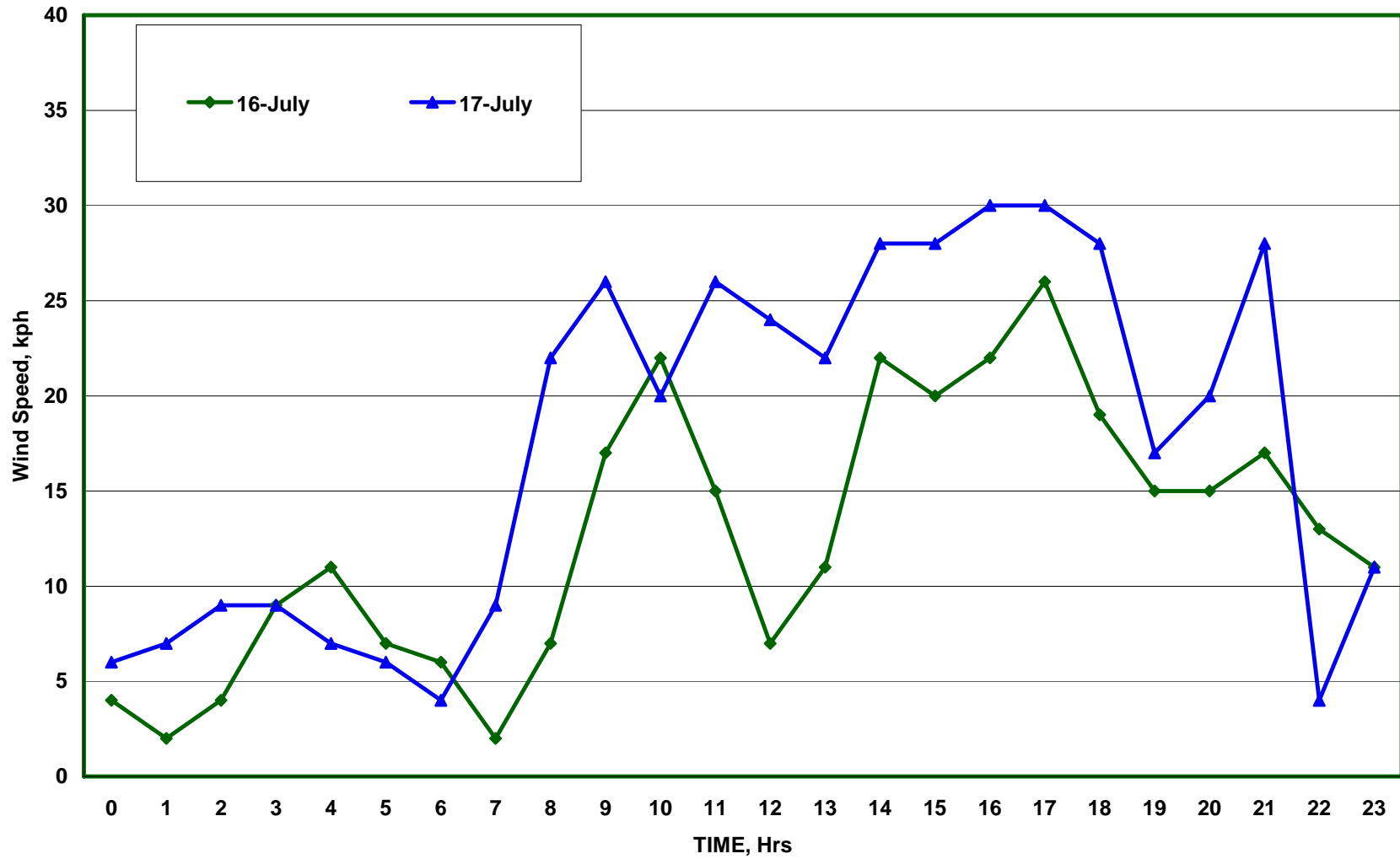


Figure 2.3 Goderich Wind speeds

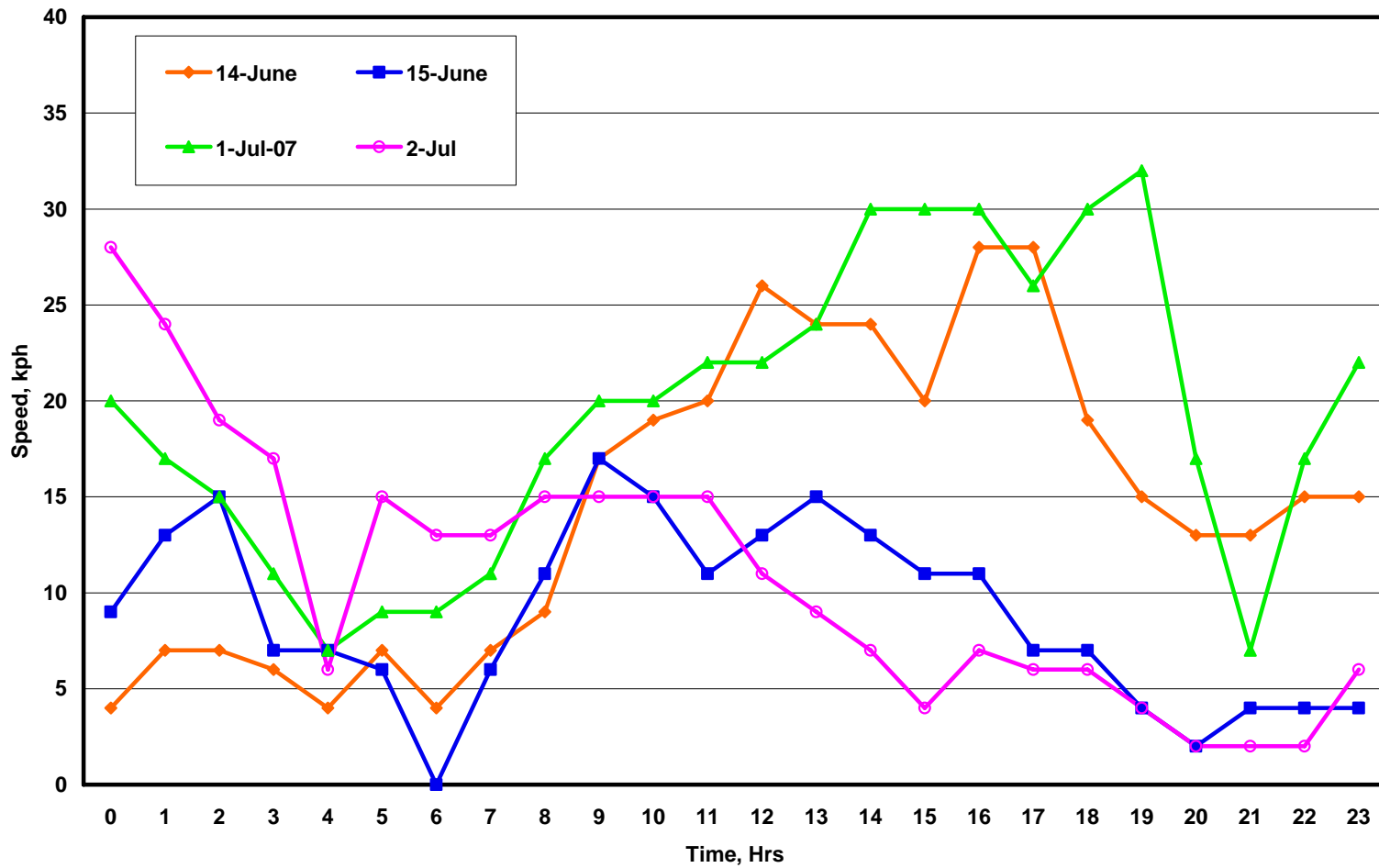
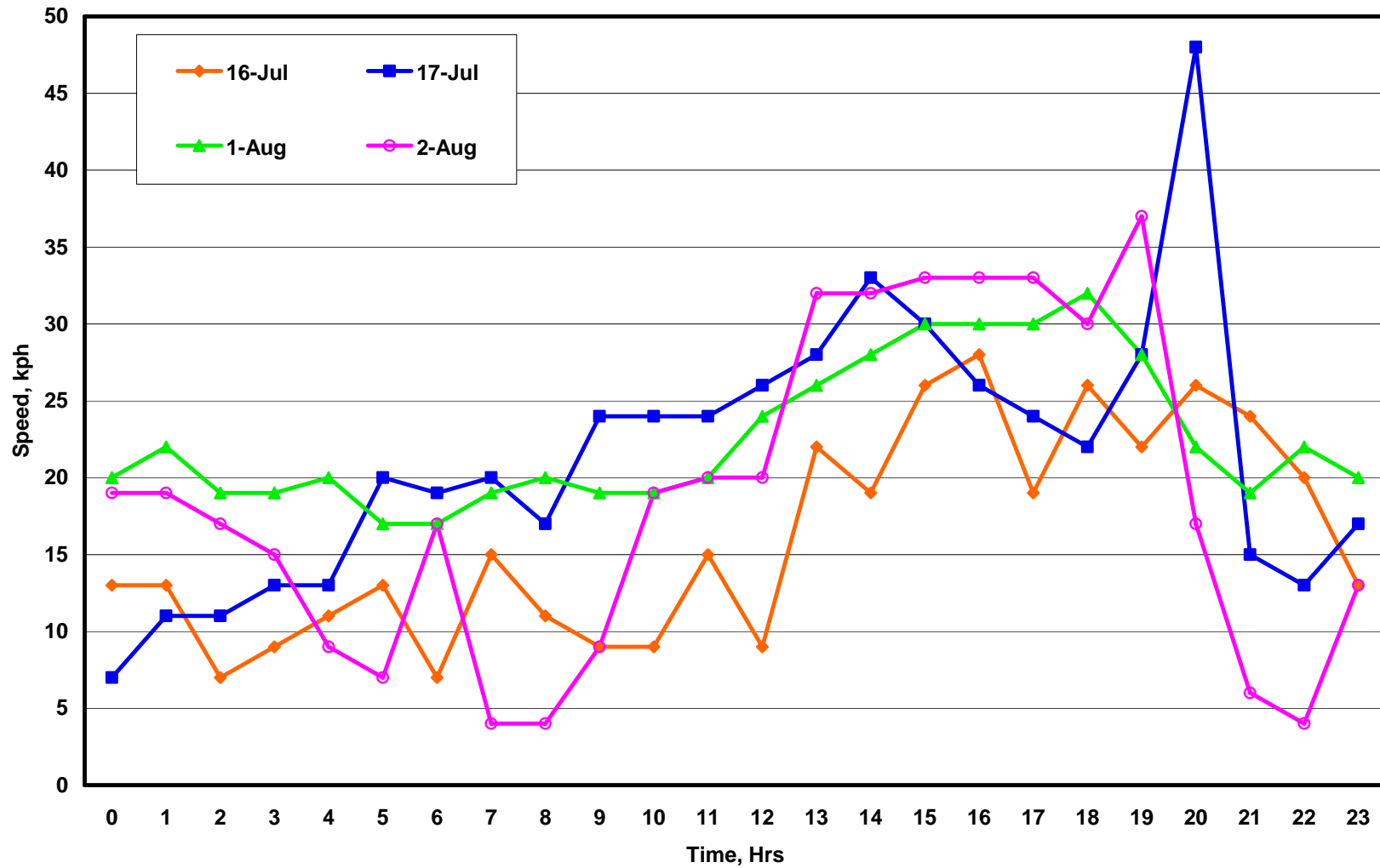
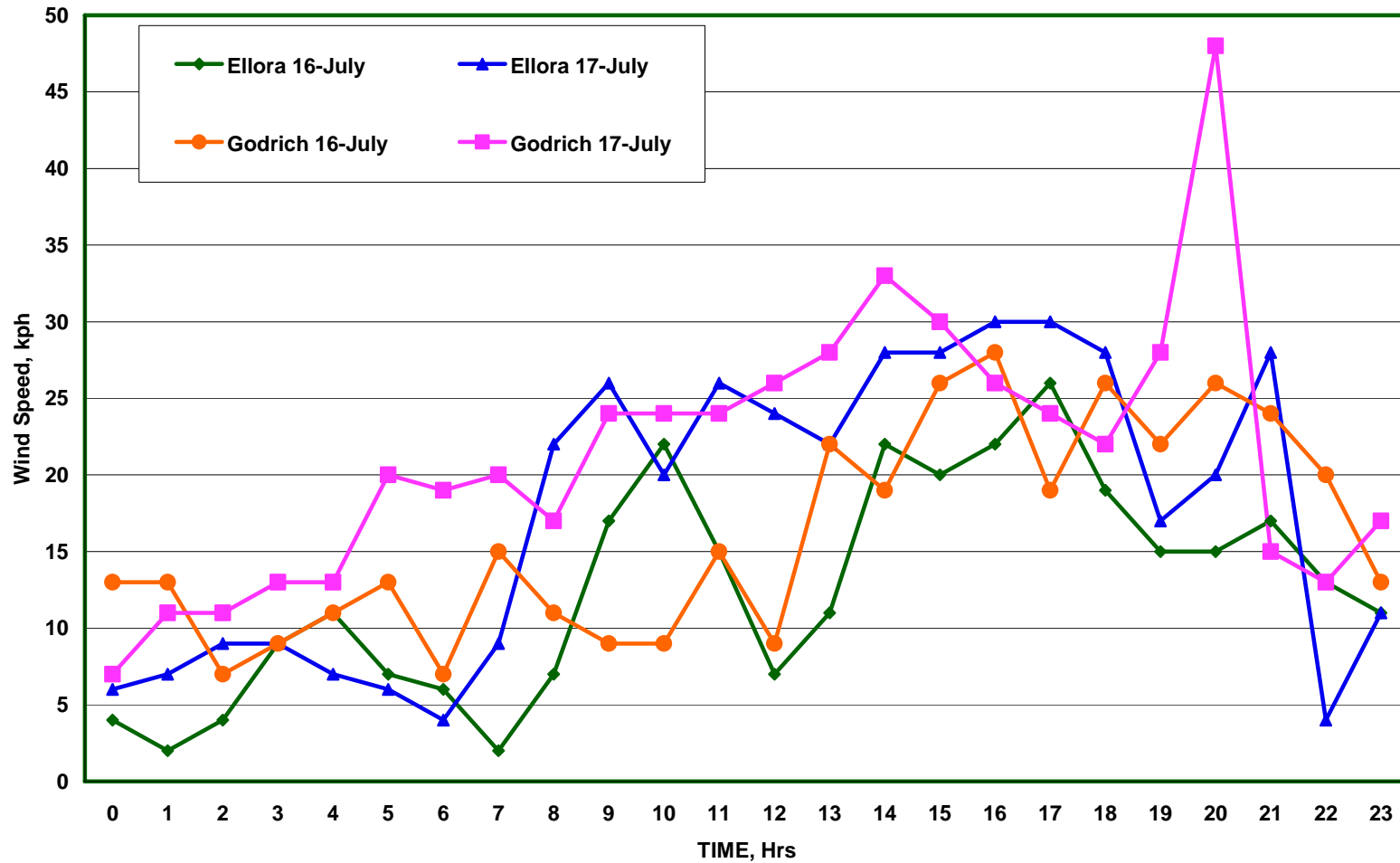


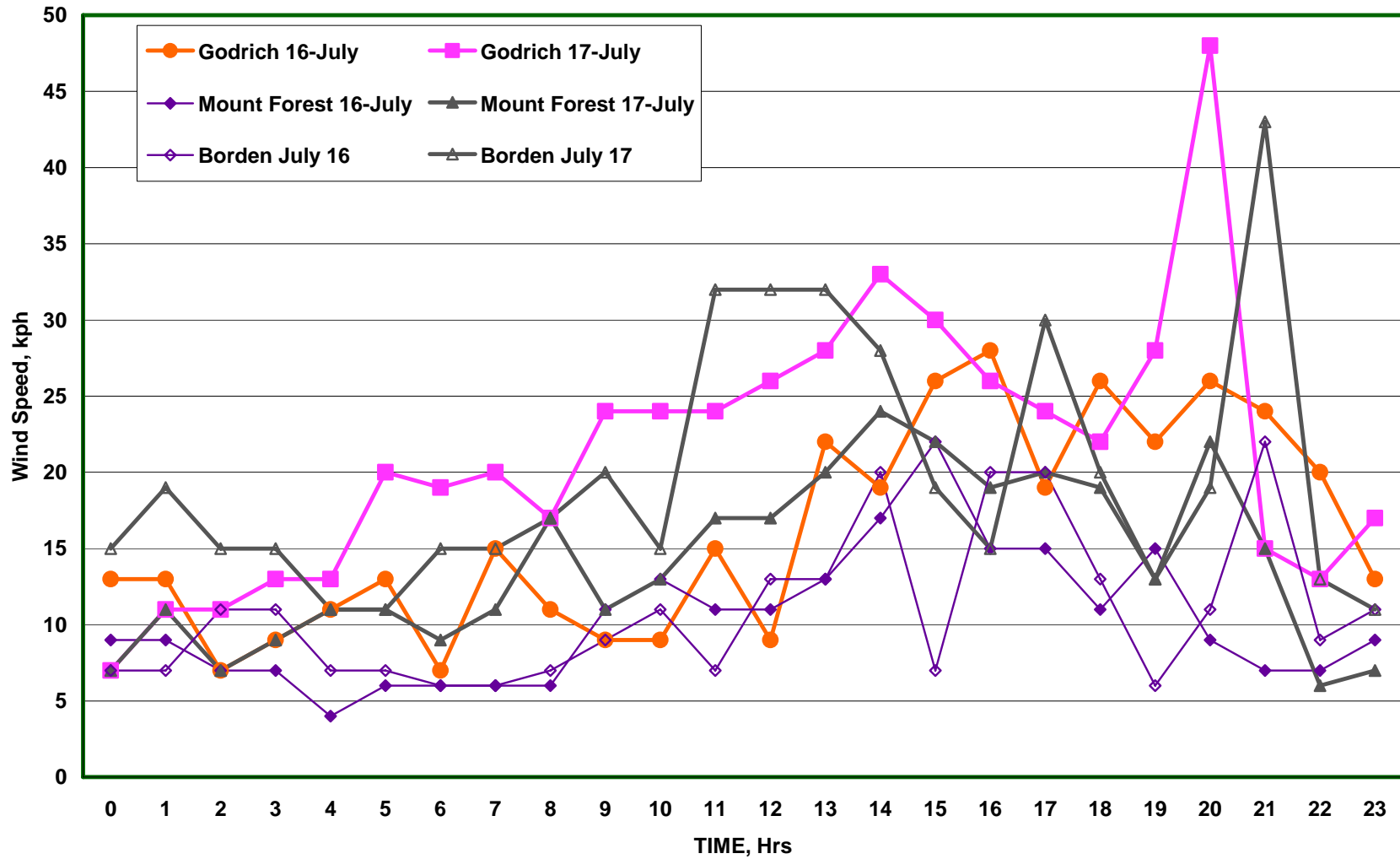
Figure 2.4 Goderich Wind speeds - 2



**Figure 2.5 Elora and Goderich Wind speeds.**



**Figure 2.6 Borden, Mount Forest and Goderich Wind speeds.**





## 2.6 SUMMARY

The doctoral dissertation of G. P. van den Berg was reviewed and comments were provided in this section. The dissertation was to provide scientific evidence for increased annoyance from wind farm during evening and night time hours. The review showed the above was not the case and the review comments are summarized below.

One of the main criticisms of the doctoral dissertation of van den Berg is that the conjectures of his research have not been supported by solid scientific data.

The major deficiencies of the doctoral dissertation are highlighted below:

- A) Simultaneous noise measurements and subjective response from a random sample of the residents were not performed other than a few anecdotal responses;
- B) The wind velocities at various heights were not conducted either at the turbines or near them to evaluate the atmospheric classes, but applied weather data from a location 40 kms away;
- C) The wind farm noise levels at receptors were unmanned and the procedure to evaluate the dominance of turbine noise may not be correct.
- D) The immission levels measured at 400 m and 1500 m distances had a large scatter to provide strong conclusions. **NOTE:** It must be pointed out that the receptor noise levels, for a substantial portion of the measurement period, were less than 40 dBA at a location 400 m away and less than 35 dBA at a location 1500 m away.
- E) The *beat* of acoustics is being identified, wrongfully, with amplitude modulations and no strong evidence was provided to show the modulation gets worse at night compared to day time in the summer.

Despite the rather strong conclusions of Reference 1 some of the basic conjectures in the dissertation merit further examination. Hence, the research of van den Berg may be considered as the catalyst that started serious discussion on many aspects of wind farm noise. Future research must therefore provide stronger scientific data to validate these different noise concerns.

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### **3.0 REVIEW OF AVAILABLE NOISE POLICIES AND GUIDELINES**

The second task for the current project was to provide an evaluation of the noise policies on Wind Turbine noise applied in jurisdictions other than the Province of Ontario.

The noise policies from different Canadian provinces, USA states and a few other countries were reviewed. The regulations from Germany and the Netherlands were gathered from other review papers. [See for example Reference 18].

General comparison of the noise regulations is presented in Table 3.1.

#### **3.1 WHO GUIDELINES FOR COMMUNITY NOISE** (Reference R1)

The community noise guidelines are the result of significant amounts of research in the relationship between noise and health. There is an understanding that noise pollution can be the cause of serious health effects through short term and long term, or cumulative, exposure. The guidelines include the values of what the World Health Organization feels to be the thresholds to health effects in various situations. The limit that has been listed in an outdoor living area, such as around a dwelling, is 50 dBA for moderate annoyance. Once the sound level has increased to 55 dBA, it is considered to be a serious annoyance. For indoors, the World Health Organization recommends the noise level to stay below 35 dBA before moderate annoyance occurs, and below 30dBA to avoid sleep disturbance at nighttime. For conditions at nighttime with an open window, the suggested limit is 45 dBA to avoid sleep disturbance. Many of the documents below reference these guidelines in the justification of selecting certain noise limits, although the Ontario Ministry of the Environment publication does not. They are also widely referred to in other literature relating to noise level limits.

**Table 3.1 Comparison of Noise Regulations.**

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
<b>ONTARIO</b>	Whichever is greatest: - Urban Areas, wind speeds below 8m/s: 45 dBA or hourly background level - Rural Areas, wind speeds below 6m/s: 40 dBA or hourly background level - Wind speeds above 8 and 6 m/s each type: wind induced background level LA <sub>90</sub> plus 7dBA or hourly background level		NPC-205 or NPC-232 whichever is higher	IEC 61400-11, to be provided by manufacturer	N/A	Impact Assessment to ISO 9613 method to be submitted prior to approval for critical points of reception up to 1000 m.
<b>Alberta</b>	Nighttime + 10 dBA	40 dBA – 56 dBA minimum	Pre-assumed based on proximity to transportation and number of dwellings OR 24 hours, 10 min. intervals in special cases	Modeling at wind speeds of 6 to 9 m/s to achieve worst-case scenario	N/A	Noise Impact Assessment Required to be submitted for application – form given in document Noise measurements, including CSLs <i>recommended</i> for speeds 4 to 6 m/s between 1.2 and 10 m above grade
<b>British Columbia</b>	40 dBA at residential property		N/A	Modeling of 8-10m/s wind speeds at 10m height to be provided by manufacturer	Siting to conform to ISO 9613-2	Risk assessment required if the difference between modeled SPL and acceptable limit is close -Measurements made if complaint is filed

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
Quebec	Sensitive Land: Type I = 45 dBA Type II = 50 dBA Type III = 55 dBA Non Sensitive Land: Type IV = 70 dBA Dwelling on Industrial Land: 55 dBA	Sensitive Land: Type I = 40 dBA Type II = 45 dBA Type III = 50 dBA Non Sensitive Land: Type IV = 70 dBA Dwelling on Industrial Land: 50 dBA	Length of time to current practiced standards – not specified. Measurements to fully cover reference intervals favoured	N/A	N/A	Measurements taken post-construction to ensure conformity, assess impact
New York (Town of Clinton)	50 dBA or Ambient + 5 dBA		Highest whole number in dBA exceeded for more than 5min per hour (requires independent certification)	IEC 61400-11 or other accepted procedures	- 500 ft from property line or road - 1200 ft from nearest off-site residence - 2500 ft from a school, hospital or nursing facility	Independent certification required before and after construction that noise limits are met.
Maine	Residential: 60dBA Comm/Ind.: 70 dBA Rural: 55 dBA	Residential: 50dBA Comm/Ind.: 60 dBA Rural: 45 dBA	Estimation based on population within 3000m radius or measurements during all hours the development will operate	N/A	N/A	Post-development one-hour equivalent measurements to be made
Pennsylvania	Fifty (55) dBA (note: this is what is in the document, not a typo here)		N/A	AWEA Standard 2.1 - 1989	1.1 x turbine height (consenting) or 5 x hub height (non-consenting)	N/A
Washington	Residential: 60 dBA Commercial: 65 dBA Industrial: 70 dBA	Residential: 50 dBA Commercial: 55 dBA Industrial: 60 dBA	N/A (Environmental noise measurement procedure is reserved)	N/A	N/A	Noise measurement only made if a complaint is filed

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
<b>Oregon</b>	Ambient + 10 dBA		26 dBA assumed	IEC 61400-11	350m minimum, or 1000m non-consenting	
<b>Michigan</b>	55 dBA or $L_{90} + 5$ dBA		55 dBA assumed, not indicated for higher levels	IEC 61400, ISO 9613 (modeling)	1.5 x height of tower including blade in top position	ANSI S12.18 (post construction), ISO 9613 model
<b>Australia</b>	35 dBA or $L_{A90,10} + 5$ dBA		Minimum of 2000 data points of background noise and wind speed pairs with a best fit curve	IEC 61400-11, must be overlaid on graph of background sound levels	N/A	Demonstration of compliance at all relevant receivers, if compliance is not demonstrated, operation will be restricted
<b>New Zealand</b>	40 dBA or $L_{95} + 5$ dBA		NZS 6801 (10-14 days of continuous monitoring)	Obtained from Manufacturer	N/A	Measurements taken if necessary, to follow same procedure as background levels
<b>UK (Britain)</b>	$L_{90, 10min} + 5$ dBA OR 45dBA OR 35-40 dBA	43 dBA or 45 dBA	Minimum 7 days continuous 10 min interval monitoring	IEA Recommended Practice – using 8m/s at 10m height	N/A	Measurements made if complaint filed; no formal impact assessment required
<b>Ireland</b>	45 dBA or $L_{90} + 5$ dBA OR 35-40 dBA if $L_{90} < 35$ dBA,	43 dBA	10 minute intervals	N/A	N/A	N/A

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
<b>Denmark</b>	45 dBA in open areas 40 dBA near residential		Annex 1 of the document; requires regression analysis of min. of 10 L <sub>Aeq</sub> values measured for at least one minute each over different wind speeds	EN 45000 standards or min. of 10 L <sub>Aeq</sub> values measured for at least one minute each over different wind speeds – see Annex 1 of document for full procedure	N/A	- Calculations of noise level at nearest property - Measurements after operation has begun or when deemed necessary, but not more than once per year
<b>Germany</b>	55 dBA/50 dBA in residential areas and 45 dBA in areas with hospitals, health resorts etc.	40 dBA/35 dBA in residential areas and 35 dBA in areas with hospitals, health resorts etc.	N/A	Recommended Practice – using 10 m/s at 10m height	-	- Calculations of noise level at nearest property, using DIN ISO 9613-2.
<b>Netherlands</b>	50 dBA	40 dBA (night) 45 dBA (evening)	N/A	-	-	-

### 3.2 NORTH AMERICAN NOISE LEVEL LIMITS AS APPLIED TO WIND TURBINES

The situation in North America in terms of noise level limits for wind turbines is currently under development. Many jurisdictions are only beginning to draft standards specifically for wind turbines, and few have gone beyond the draft stage. This is true for both the United States and Canada, where wind is still a relatively under-utilized energy source. There are a number of examples of noise level limits below from the Northern U.S. States, and some Canadian provinces, and they represent the variability from one jurisdiction to the next.

#### 3.2.1 Ontario - Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators (Reference R2)

The Ontario Ministry of the Environment has produced a document listing noise requirements for wind turbines. The document segregates development into three separate classes, the first two referring to urban environments, and the third referring to a rural environment. The sound level limits are dependent not only on their classification, but on the wind speed also. Where wind speeds are lower than 8 m/s in an urban environment, the hourly equivalent sound level from the wind turbine facility must not exceed 45 dBA or the hourly background sound level, whichever is greater. Similarly, in a rural environment where wind speed is less than 6 m/s, the hourly equivalent sound level must not exceed the greater of 40 dBA or the hourly background sound level. In the cases where the wind speeds exceed these levels, rather than a fixed limit, the sound level is permitted to be the wind induced background sound level,  $L_{A90}$ , plus 7 dBA. This is demonstrated in the Table 3.2 below.

**Table 3.2. Ontario Noise Assessment Limits**

Wind Speed (m/s)	4	5	6	7	8	9	10	11
Wind Turbine Noise Criterion NPC-232 (dBA) (Rural)	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA) - (Urban)	45	45	45	45	45	49	51	53

The noise limits apply to both daytime and nighttime periods, with the level being measured at the nearest point of reception: a location within 30 m of an existing or zoned for future dwelling. After a distance of 1000 m between the wind turbine facility and the point of reception, a detailed noise assessment is not required.

### **3.2.2 Alberta - EUB Directive 038 Noise Control** (Reference R3)

Of all the documents reviewed, the sound level limits for wind farms are perhaps the most complicated to determine in the province of Alberta, Canada. Primarily, the permissible sound level, PSL, depends on the location of the nearest residences. If there are no dwellings within 1.5 km, the limit is a fixed 40 dBA (this corresponds to an increase over the assumed ambient sound level of 35 dBA in rural areas). However, if there are places of residence, the PSL must be determined by the following equation:

$$\text{PSL} = \text{Basic Sound Level} + \text{Daytime Adjustment} + \text{Class A Adjustment} + \text{Class B Adjustment}$$

The Basic sound level is the main component of the sound level limit and ranges from 40 dBA to 56 dBA, depending on the receiving property, and is selected from a table. The daytime adjustment allows the addition of 10 dBA to the PSL during the time period of 7 a.m. – 10 p.m. The other adjustments, Class A and Class B, require technical verification to be applied, and are only done so in specific circumstances. In order to properly determine the ambient noise level and the wind farm development's noise emissions, certain procedures must be followed which are documented in the directive. For example, the ambient sound level measurement requires continuous monitoring over a 24-hour period, 15m away from the nearest dwelling. The environmental conditions at the time of the measurements are also strictly detailed. Although their sound level limits are higher than the MOE limits, similar documentation is required, such as a noise impact assessment.



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**3.2.3 *British Columbia - Land Use Operational Policy: Wind Power Projects***  
(Reference R4)

The British Columbia policy regulating noise from wind turbines enforces a fixed limit of 40 dBA during all hours of the day. This limit is more restrictive than in Ontario, where allowances for higher sound levels are made when the wind speed increases. This limit is to be measured at the exterior of the nearest permanently occupied residence and/or the property line of undeveloped land zoned for future residential use. The siting must conform to ISO 9613-2, which is referenced by other jurisdictions, including Ontario, for use in impact assessment. The modeling is also similar to other jurisdictions, requiring the sound power level (PWL) to be estimated for 8-10 m/s wind speeds at a 10 m height. Should the modeling demonstrate that the estimated level is close to the acceptable limit, the policy requires that a risk assessment be conducted prior to approval. Testing of the sound levels of the facility post-construction is performed if a complaint is filed.

**3.2.4 *Québec - Instruction Memo 98-01 on Noise (Note: revised as of June 9, 2006)***  
(Reference R5)

Quebec does not have a specific document relating only to wind turbines; the applicable paper discusses noise from all fixed sources. Different limits have been assigned based on the land use of the receiving property and the residual level of noise in the area. The location of measurement is at a distance 3 m or more from reflective structures, and 0.5 m from an open window. All sound levels averaged during a period of one hour must comply with these limits. There are two main categories of land use: sensitive zones (i.e. residential, hospitals, schools) and non-sensitive (agriculture and industrial use) zones. See table below for limits. In the case of a dwelling on agricultural land, the limits for a sensitive zone apply. For dwellings on industrial land, a 50 dBA nighttime limit and a 55 dBA daytime limit will apply. In terms of sensitive areas, the noise limits are comparable to those in Ontario, although there are different levels for day and night. However, an exception is given in the case of industrial and agricultural land, unless a dwelling exists, for the sound level limits to be much higher. The sound that is measured at the receiving property is based on an equation given in the document, accounting for the equivalent sound level of the source, and corrective factors to account for impact noise, tonal noise and

special situations. However, the length of time that applies is up to the discretion of the person performing the evaluation, and should correspond to the current practice methods. Similarly, when measuring background noise, measurements taken that cover the full reference range are favoured, but not required. Post construction, measurements must be taken to ensure the compliance of the facility with the appropriate limits.

**Table 3.3 Noise Regulations in Quebec**

<b>Zone</b>	<b>Night</b>	<b>Day</b>
I – Sensitive – Single family dwellings, schools, hospitals	40dBA	45dBA
II – Sensitive – Multi-residential and camping areas	45dBA	50dBA
III – Sensitive – Commercial use and park land	50dBA	55dBA
IV – Non-sensitive – Industrial or Agricultural	70dBA	70dBA

**3.2.5 Oregon - Revising Oregon's Noise Regulations for Wind Turbines**  
(Reference R6)

Oregon has recently undergone a revision to its existing noise standards, which were last updated in the 1970s. There are two tests, or limits, that apply in the case of wind turbine developments, the Table 8 test (refers to Table 8 in the regulation) and the ambient degradation test. The authors of the revision have taken steps to coordinate their standard with that of the British and Australian guidelines on wind turbine noise. They have assumed a standard ambient background  $L_{50}$  of 26 dBA, although extensive documentation can be submitted for background noise greater than this level. The noise level limit is not allowed to increase the ambient noise levels by 10 dBA in any one hour, thus having an assumed limit of 36 dBA, which is lower than the MOE limits. It is also low enough to respect the WHO guidelines for indoor levels without accounting for sound reduction through walls. This limit applies to both daytime and nighttime, just like the MOE limits. However, unlike the Ontario requirements, there are also setbacks that must be adhered to; a minimum of 350 m for a consenting owner, and 1000 m between the nearest wind turbine and the property of a non-consenting owner. The methods of evaluating the sound created by the wind turbine development use the same methods that the majority of manufacturers provide to make things easier. The project must be evaluated under the maximum

sound power level conditions according to IEC 61400-11 (8 m/s at 10 m height), but no correlation between 10 m and hub height is assumed.

**Table 3.4 Oregon’s Table 8 Limits, dBA**

Statistical Descriptor	Daytime (7 a.m. – 10 p.m.)	Nighttime (10 p.m. – 7 a.m.)
L <sub>50</sub>	55	50
L <sub>10</sub>	60	55
L <sub>1</sub>	75	60

**NOTE:** Maximum Permissible levels for New Industrial and Commercial Noise Sources, dBA - As in Bastasch, Noise-Con 2004, originally from OAR 340-35-035.

### **3.2.6 Pennsylvania - Wind Farm Model Ordinance Draft 12-08-06** (Reference R7)

The draft document developed in Pennsylvania is a model document prepared for the use by different local municipalities. It is not the regulation for the entire state. Local municipalities can use the draft document to prepare their own policies and guidelines. There is only one limit in the Pennsylvania draft, which applies to both daytime and nighttime. The sound level limit is slightly unclear however, because it states that the audible sound “shall not exceed fifty (55) dBA” (note that this has been correctly recorded here, the discrepancy between the written word and the numerical value given in parentheses). This value is much higher than the value given in the MOE regulation, and also equals the WHO recommendation for serious annoyance in an outdoor setting. [See Reference R1]. There is no mention or consideration of ambient sound levels, but waivers to this sound level may be considered. It also does not mention whether this is an hourly limit or not. The point of receiving is considered to be the “exterior of any occupied building on a non-participating Landowner’s property.” There are also associated setbacks that must be followed. The distance between a wind turbine and the nearest building on the same property must be a minimum of 1.1 times the turbine height. The distance between a turbine and the nearest occupied building on a non-participating property must be at least 5 times the hub height of the turbine. These setbacks exist in response to both safety and noise related issues.

**Table 3.5. Pennsylvania Draft Ordinance**

Source	Receiving Property Designation					
	Residential (Class A)		Commercial (Class B)		Industrial (Class C)	
	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
Class C	60 dBA	50 dBA	65 dBA	55 dBA	70 dBA	60 dBA

**Note:** Daytime is considered to be 7am – 10pm  
Nighttime is considered to be 10pm – 7am

**3.2.7 Washington - Chapter 173-60 WAC Maximum Environmental Noise Levels**  
(Reference R8)

In Washington State, there is no specific regulation for wind turbine noise, so sound levels must comply with the limits in the environmental noise legislation. This results in noise limits that are the highest among those reviewed here (along with Maine), much higher than the MOE limits. Noise level limits are dependant upon the designation, or class, of both the source property and the receiving property. Wind turbines, as a source, would fall under neither Class A, residential, nor Class B, commercial; therefore they would be considered Class C. The hourly sound levels must not exceed the listed measures anywhere within the property line of the neighbouring property. However, it is also mentioned that local governments should adopt their own noise policies. Chapter 173-58 WAC details the proper sound level measurement procedures to follow.

**3.2.8 Michigan - Michigan Wind Energy System Siting Guidelines Draft #8**  
(Reference R9)

The Michigan wind energy draft is meant to apply to smaller local governments and non-urban areas that do not have other existing guidelines in place. There are different guidelines for small, on-site use wind turbines, and larger developments meant for grid energy use.

The Michigan guideline considers the measure of the ambient sound level to be  $L_{90}$  and it is assumed to be less than 55 dBA in most cases. The guidelines state that the sound level generated by the turbines should not exceed 55dBA at any property line, unless with written

consent. This level is similar to the one developed by the State of Pennsylvania (see above). During any one hour, this is not to be exceeded for more than three (3) minutes. Should the ambient sound level be greater than 55dBA, then the sound level limit is  $L_{90} + 5\text{dBA}$ ,  $L_{90}$  as the measured ambient sound level. For demonstration of the compliance to these limits, a submission following IEC 61400 and ISO 9613 methods must be completed for project approval, and within 60 days of the project's completion, the levels must be verified to ANSI S12.18 by a professional third party. The State of Michigan is the only other jurisdiction among those reviewed that requires submission of noise impact according to ISO 9613 like the Ontario MOE requirements. However, the noise level limits are much higher than the MOE limits.

**3.2.9 Maine - Chapter 375 No Adverse Environmental Effect Standard of the Site Location Law**  
 (Reference R10)

This is another example of a state that has written a standard for use where local governments have not written their own. Local standards take precedence over the state limits unless they contain values over 5 dBA higher for the same situation. As with the Washington sound level limits, the noise limits within this document apply to all environmental noise, including wind turbines, resulting in much higher values. The noise limits apply to new and expanding developments and are measured at the property line, but no specific information is provided on how the sound levels from wind farms are to be modeled. The limits vary based on the zoning of the receiving property or the ambient sound level, and are different for day and night. The noise limits are summarized in the Table 3.6.

**Table 3.6 Regulations in Maine**

<b>Receiving Property</b>	<b>Daytime Sound Level Limit (7am – 7pm)</b>	<b>Nighttime Sound Level Limit (7pm – 7am)</b>
Any location that is not zoned for commercial, transportation or industrial	60 dBA	50 dBA
Any location that is zoned for commercial, transportation or industrial	70 dBA	60 dBA

These limits apply unless the ambient sound level prior to development is equal to or less than 45 dBA during the daytime hours and 35 dBA during the nighttime hours, such as in a rural environment. Should this be the case, the limits are required to be 55 dBA during the day and 45 dBA during the night; a 10dBA increase, regardless of the zoning of the receiving property. There are two methods allowed to demonstrate the level of the ambient sound, by performing measurements, or, if the population within a 3000 m radius of the property is greater than 300 people, the state allows the assumption that the ambient level exceeds 45 dBA during the day and 35 dBA at night. Additionally, if it can be proven that the development will not emit sound levels greater than 50 dBA during the day and 40 dBA during the night, there is no requirement to estimate or measure the sound levels.

There are further requirements for short duration repetitive sounds and tonal sounds. There are also regulations on the personnel carrying out the measurements, the instrumentation and calibration necessary, and the location, configuration and environment conditions for the microphones, but not necessarily in the specific case of applying the measurements to wind farms.

***3.2.10 New York - Power Naturally: Examples of NY Local Government Laws/ Zoning Provisions on Wind***  
(Reference R11)

The state of New York does not have a standard for wind turbine noise, but relies on local governments to develop their own, which many have. The town of Clinton, NY, is one such municipality, and is a good indication of what the standards in New York State are like. The limit, which applies at any time of the day, is  $L_{10} \leq 50\text{dBA}$ , meaning that in any one hour, 50 dBA can be equaled or exceed only ten percent of the time. The sound level is measured at the nearest residence, located off-site, which may or may not include more than one property. If the owner consents to a higher threshold of noise, a waiver can be granted allowing an increase to the noise level limit. If the ambient sound, which is defined as the highest whole number in dBA exceeded for more than 5 minutes per hour, is greater than 50 dBA, then the sound level limit is the ambient sound level plus 5dBA. These levels are higher than the MOE limits, but remain

just below the level of moderate annoyance for outdoor noise of 50dBA listed in the WHO Community Noise document.

### **3.3 NOISE LIMITS FROM EUROPE**

Europe has long been at the forefront of developing and utilizing wind energy as an energy source. It is not surprising that they have been able to develop noise limit standards to a higher degree than North America. It does not mean that they are more complicated; in fact, they are often simpler than North American noise limits. The following are some examples of noise level limits of wind farms from European countries.

#### **3.3.1 UK - ETSU-R-97: *The Assessment and Rating of Noise from Wind Farms*** (Reference R12)

The document produced by the Working Group on Noise from Wind Farms is perhaps the most comprehensive document of all the ones reviewed here. It covers the history and philosophy of developing noise limits, as well as a thorough explanation of the current limits. The document regulates a separate limit for daytime and nighttime noise levels. These are in part based on the background noise level,  $L_{A90, 10min}$ , which is determined by continuous monitoring of ten minute intervals over a period of time, correlated with different average wind speeds measured over the same period. There is no distinction between zoning or the use of the receiving property as in the Ontario MOE limits.

The principle of the limits is that the wind farm noise is limited to 5 dBA above the wind dependent background noise level, subject to a minimum value at low wind speeds. During the daytime, this minimum value in low noise environments is not to be lower than a range between 35 dBA and 40 dBA, depending on the number of dwellings and the effect on the amount of energy produced. At night, this minimum value is 43dBA. Both of these limits are recommended to be increased to 45 dBA in cases where there is financial benefit to those involved. As with other standards, a 5 dB penalty is incurred if tonal characteristics occur. Should this appear to be the case, a tonal assessment must be performed, consisting of 2 minute

measurements. The document does not require an impact assessment of the development to be submitted.

### **3.3.2 *Ireland - Wind Energy Development Guidelines*** (Reference R13)

Ireland has adopted noise limits that are similar to the UK limits for wind turbines. The daytime limit is allowed to be the maximum of 45 dBA or 5 dBA above the background level, L<sub>90</sub>. However, if the current level of background noise is very low, below 30dBA, the noise level limit will fall in the range of 35 dBA to 40 dBA. The standard does not state how this limit will be determined. The nighttime limit is fixed at 43dBA. These noise levels are comparable to the Ontario MOE limits. The Irish Guidelines have no set-back limits. Instead it states and we quote, “In general noise is unlikely to be a significant problem where the distance from the nearest turbine to any noise sensitive property is more than 500 m.” [Reference R13]. The document has stated that in order to determine the ambient sound level, measurements should be taken at ten minute intervals, however, it has not dictated how the wind farm noise level should be predicted or what steps to determine the impact of the wind farm should be taken.

### **3.3.3 *Denmark - Document: Statutory Order From the Ministry of the Environment No. 304 of May 14, 1991, On Noise From Windmills*** (Reference R14)

Denmark’s noise limits are fixed, ambient conditions having no effect, and apply to both daytime and nighttime with no distinction. This is in contrast to the MOE limits, which may depend on both the wind speed and the hourly background level; however, the actual sound level limits have a direct comparison to Ontario’s. When the wind farm is located in the open country, the outdoor sound level limit is 45 dBA at the nearest neighbouring property, considered to be any residential building other than the “private house of the windmill owner”. For wind farms closer to residential areas, the fixed limit is 40 dBA.

### **3.3.4 *Germany - Document: Lärm (Technische Anleitung Lärm, Germany), 1998*** (Reference R15)



The German noise limits are defined in the above document and are outlined in Table 3.7 below.

**Table 3.7. German Noise Regulations.**

Area	Day Time	Night Time
Industrial Area	70 dBA / 65 dBA	70 dBA / 50 dBA
Mixed residential area and industry or Residential areas mixed with industry	60 dBA	45 dBA
Purely residential areas with no commercial developments	55 dBA / 50 dBA	40 dBA / 35 dBA
Areas with hospitals, health resorts etc.	45 dBA	35 dBA

Calculation of sound propagation is done according to ISO 9613-2. All calculations have to be done with a reference speed of 10 m/s at 10 m heights.

**3.3.5 Netherlands: Bseluit van 18 oktober 2001, houdende regels voor voorzienen en installaties; Besluit voorzienen en installaties milieubeheer; Staatsblad van het Koninkrijk der Nederlanden 487**  
(Reference R16)

Noise regulations specific to wind turbines in the Netherlands were issued in 2001, but are currently under review by the Dutch authorities. The 2001 wind farm noise limits followed a wind speed dependent curve and are shown in Table 3.3.2 for night time noise limits. The limit for day time started at 50 dBA and for evening hours, the limit started at 45 dBA and increased to 50 dBA for a speed of 12 m/s.

**Table 3.8. 2001 Netherlands Noise Assessment Limits – Night time.**

Wind Speed at 10 m height (m/s)	1	2	3	4	5	6	7	8	9	10	11	12
Wind Turbine Noise Criterion, dBA	40	40	41	41	42	42	43	44	46	47	48	50

As noted above, the 2001 assessment process is currently under review. In the interim, the Dutch authorities use their established general limits, not specific to wind turbines, of 40 dBA (night), 45 dBA (evening) and 50 dBA (day).

### **3.4 WIND FARM NOISE LIMITS FROM AUSTRALIA AND NEW ZEALAND**

The wind farm noise limits of these two countries relate more to those of the European countries rather than North America. They require extensive data collection for the determination of ambient sound levels, and the sound level limits themselves are among the lowest, being developed in accordance with the World Health Organization document Guidelines for Community Noise. The standards as written are much more detailed in their requirements, and thus are of great value when reviewing noise standards for wind farms.

#### ***3.4.1 Australia - Planning Bulletin 67: Guidelines for Wind Farm Development and Environmental Noise Guidelines: Wind Farms*** (References R17 and R18)

There are documents from both Western and Southern Australia; however, there is only one set of noise limits since the Western Australia guidelines reference the South Australian noise limits. The South Australian guidelines have elected to define fixed limits that must be followed, and are among the strictest that are reviewed here. The limit during the daytime is 35 dBA or the background noise plus 5 dBA,  $L_{A90, 10} + 5$  dBA. The other jurisdiction that has a comparable noise level limit is the American state of Oregon. Both Australia and Oregon have limits that are more strict than Ontario. In order to determine the ambient levels, extensive data collection of noise levels over continuous 10-minute intervals must be examined according to a regression analysis. Wind speeds must be measured at 10m above the ground and also analyzed over the same periods. In order to determine the sound level limit compliance, the sound is measured not at the property line, but at a distance of up to 20 m away from the nearest house. In addition, demonstration is required that shows the operational sound levels do not exceed the

predetermined limits or else restrictive measures may be taken to limit the operation of the wind farm.

**3.4.2 New Zealand - NZS 6808: 1998: Acoustics – The Assessment and Measurement of Sound From Wind Turbine Generators**  
(Reference R19)

New Zealand also has a fixed sound level limit, as with other countries. At any residential home, the sound level limit outside of the house must not exceed 40 dBA. This limit has been selected to achieve an indoor sound level that corresponds to the values recommended in the WHO Guidelines for Community noise. If the background noise,  $L_{95}$ , exceeds 35 dBA, then the sound level limit is permitted to be  $L_{95} + 5$  dBA. These levels are higher than the strict limits of Australia and Oregon, and are comparable to the Ontario and Danish sound level limits. This limit is to apply at the property line of the nearest residential property, or the “notional boundary” if the dwelling is located on a large rural property. The standard allows the sound levels from the wind farm development to be estimated using the sound power levels supplied by the manufacturer, but for determination of the ambient sound levels, extensive data collection over a period of ten to fourteen days is required. Post-installation verification is not always required by the standard.

**3.5 DISCUSSION**

The assessment of wind farm noise and their impact on sensitive receptor locations as applied in different jurisdictions were described above. The main differences between the different regulations and guidelines are twofold:

- a) The acceptable noise limits; and
- b) The evaluation of receptor noise levels from the cumulative operation of the turbines in the wind farm.

The commonality among the regulations and guidelines is quite striking. All of them accept the IEC Standard 61400-11 (Reference 26) procedures to establish the sound power levels of wind turbines as well as the determination of the hub-height and/or the 10 m high wind speeds within

the operating range of the wind turbines. In addition, none of them consider the effect of atmospheric classes on night time operational character of the wind farm such as higher-than-expected wind speeds at hub-height compared to the conventional wind-shear prediction methodologies.

It is seen therefore, that the main difference between the regulations and guidelines is the noise limits and hence a comparison table is given below in Table 3.8 below. Table 3.8 summarizes only the night time noise limits. Note that direct comparisons of limits may not be appropriate as different jurisdictions have different legal, procedural and assessment frameworks.

**Table 3.8. Approximate Ranking of Noise Regulations (Night time limit, dBA).**

<b>Jurisdiction</b>	<b>Noise Limit, dBA</b>
Australia	35 and adjusted higher with wind speeds
Germany and Oregon, USA	35 to 36
Alberta, British Columbia, Quebec, Denmark, and Netherlands (Interim)	40
United Kingdom, Ireland, Ontario and New Zealand	40 and adjusted higher with wind speeds
New York, Maine, Pennsylvania and Washington, USA	50 and higher

### **3.6 SUMMARY**

Regulations and guidelines from different jurisdictions in North America, Europe and Australasia were highlighted in this section. These are some of the examples of different assessments of noise impact from wind turbines and wind farms. It was shown that some jurisdictions have special legislation concerning wind turbines, while others apply general recommendations. Different descriptors such as  $L_{Aeq}$  or  $L_{A90, 10 \text{ min}}$  were used to quantify wind turbine noise levels. The noise levels could be either absolute values or related to the background noise level. The background noise levels could be standardised, measured or related to ambient wind speeds. The review of the regulations and guidelines of the jurisdictions investigated showed that the Ontario, Canada assessment process is similar to other jurisdictions.



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## **4.0 REVIEW OF AVAILABLE LITERATURE**

A substantial portion of information, both scientific and non-scientific is available in the open literature. The literature review focussed mainly on the following:

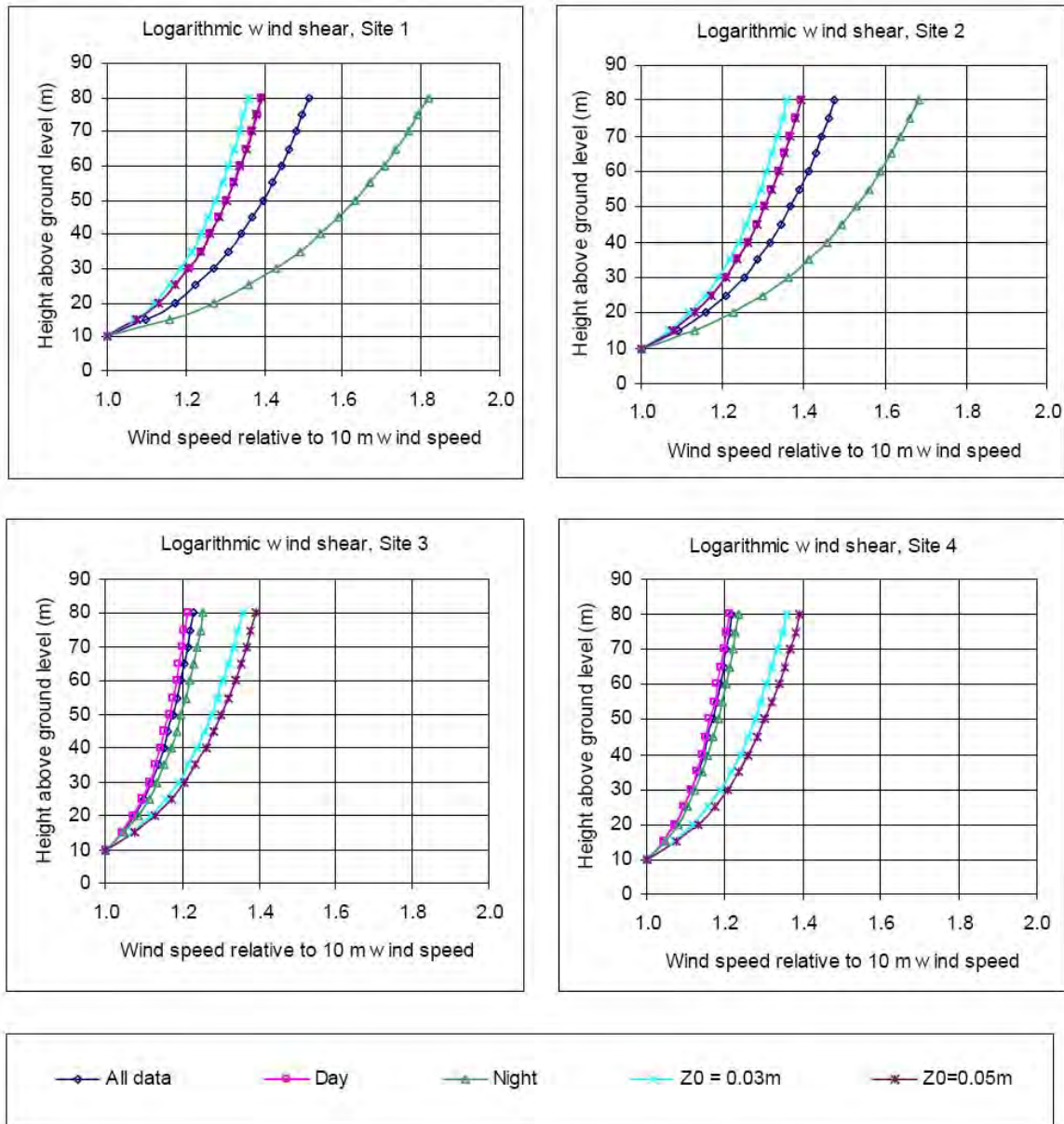
- I) Metrological effects on wind turbine noise generation;
- II) Assessment procedures of wind turbine noise levels and their impact;
- III) Particular characteristics of wind farm noise; and
- IV) Human responses to wind farm noise levels.

**NOTE:** The literature review did not consider material that was available after June 2007.

The exact noise generation mechanisms of wind turbines and control techniques of wind farm and turbine noise were not reviewed by the current investigations. Relevant databases such as journals through ScholarsPortal, internet and conference proceedings were searched for the literature. Proceedings from a few conferences were searched also. It must be pointed out that conference papers are usually accepted without proper peer-reviews. Only a few articles were available and are listed in the main reference list. The results of the review are summarized below.

### **4.1 METEOROLOGICAL EFFECTS**

The paper by P. Botha of New Zealand has shown the effects of weather conditions on wind speed profiles with height (Reference 22). This is the only paper, to our knowledge, that has scientifically shown variation of wind speeds with heights from measurements conducted at four sites – two (2) in New Zealand and two (2) in Australia. The measurements were conducted for a period of one year. The two Australian sites (Sites 1 and 2) were flat terrain and the two New Zealand sites (Sites 3 and 4) were complex terrain. Wind speeds were collected in 10 minutes intervals and the composite results from Reference 22 are reproduced below as Figure 6.1.



**Figure 4.1. Wind speed profiles at 4 different sites**

**(From Reference 22 – Figure 1)**

Five graphs were plotted for each site: Composite profile for all day data, profile for day data, profile for night data, IEC standard logarithmic profile with the shear coefficient from observed site conditions ( $Z_0 = 0.03$ ) as well as the standard shear coefficient,  $Z_0$ , of 0.05. The results do indicate that for some terrains, the hub-height wind speeds can be more at night time than during

day time when compared to the 10 m height wind speeds. However, the local conditions determine the meteorology and one cannot, as analysed by van den Berg, apply information from far-off sites to local conditions. Further, for the terrains in Australia, the Sound Power Levels at night time would be around 2 dBA more than predicted from standard procedures from day time profiles. It must also be highlighted that the measurements of Reference 22 clearly showed the wind profiles were nearly identical between day and night time for the complex terrains of New Zealand.

The main conclusions of this section are: a) wind shear is an important parameter that must be accounted for appropriately in any assessment; and b) the effect of meteorology is highly localized and strong conclusions cannot be easily transferred from site to site.

#### **4.2 ASSESSMENT PROCEDURES OF WIND TURBINE NOISE LEVELS**

Papers by Botha (Reference 22), Sloth (Reference 23) and Sondergaard (Reference 24) are examples of work undertaken to look into the assessment procedures currently applied in many jurisdictions. These three papers evaluate the application of sound power levels of wind turbines standardized to a 10 m height wind speed. The main conclusion of these papers is that the normal procedure of basing the analysis and assessment on the standardized sound power levels is not sufficient. Sloth shows a method to incorporate the relevant sound immission data with appropriate uncertainties accounted for so as to minimize noise annoyance. One such method is suggested in Appendix F. Sondergaard has also pointed out that additional research is required to account for many of these deficiencies. References 27 and 28 showed that many of the propagation models have uncertainties associated with them and can produce “less than accurate” results if local weather conditions are not properly modelled.

One of the main criticisms about noise assessment process of wind farm application is that the sound power levels of wind turbines are measured and reported following the procedures of the IEC-Standard [Reference 26]. It must be noted that the IEC 61400-11 standard for wind turbine noise is a measurement standard and is primarily intended to define how manufacturers obtain



and report the sound power from wind turbines under standardized wind shear conditions. It does not prevent one from adjusting the sound power to reflect the actual site specific wind shears obtained from testing.

### **4.3 PARTICULAR CHARACTERISTICS OF WIND FARM NOISE**

Two main issues are usually discussed regarding the source characteristics of noise generated by wind turbines – low frequency or infra sound and the swishing (thumping) sound normally termed as the amplitude modulation phenomenon.

The measurement results from wind turbines, such as the data reported by van den Berg (Reference 1) and Howe and McCabe (Reference 28) show the absence of significant low frequency components and the same conclusion is highlighted by Regan and Casey ((Reference 25) in their primer on wind turbine noise aspects. The results of Reference 1 (van den Berg’s dissertation) show that the infra-sound levels, even if present, are well below the threshold of perception.

The nature of the amplitude modulation phenomenon and its relationship to the acoustical *beating* phenomenon was already discussed in Section 2.4. The different principles of these phenomena will not be discussed further. Due to the nature of the amplitude modulation phenomenon, the swishing or thumping exists all the time. Only van den Berg has attempted to show that the modulation gets stronger at night time. Our review of van den Berg’s work was presented in Section 2. We were unable to find other works in the literature that provide evidence for increased modulation at night time. The only effect, discussed in the next section, of the phenomenon is the modulated sound becomes audible at night time. This could be due to quieter ambient sound at night time. As Reference 18 states, “In summary, the modulation in the noise from wind turbines is not yet fully explained and will not be reduced in the near future and is therefore a factor of importance when discussing noise annoyance from wind turbines.”

Reference 30 has addressed the issues connected with modulation. One of its principal findings is and we quote, “the common cause of complaint was not associated with low-frequency noise,

but the occasional audible modulation of aerodynamic noise, especially at night. Data collected showed that the internal noise levels were insufficient to wake up residents at these three sites. However, once awoken, this noise can result in difficulties in returning to sleep.” Reference 30 does not use the term “beating” to describe the amplitude modulation that has been observed as well as measured. It has been referred to simply as “aerodynamic modulation.” Reference 30 also points out that the many mechanisms hypothesized by van den Berg (Reference 1) for the modulation behaviour are debatable. It was shown in Section 2 during the current investigation that the data provided by Reference 1 do not support its findings. Further, no support was seen for the modulation behaviour to get stronger under stable atmospheric classes at night time as postulated by van den Berg. The same points were presented in Section 2 of this report. Finally, Reference 30 discussed the many possible mechanisms that can cause the amplitude modulation as well as provided measurement results to show that modulation can produce changes in noise levels of the order of 10 dB. It concluded that detailed research is required to settle many of the unknowns that can cause the amplitude modulation.

#### **4.4 HUMAN RESPONSES TO WIND FARM NOISE LEVELS**

A considerable body of literature is available on this subject, both scientific and anecdotal. Only a few of the scientific and review articles, References 5, 12, 18, 20, and 25, are highlighted in the current study.

According to Reference 25, the only health effect of wind turbine noise is annoyance. Sheppard et al. (Reference 12) conducted a laboratory study with unbiased subjects and played different sounds including wind turbine noise at various levels. Since the study was conducted in early 80s, the old type wind turbines were included in their investigations. Their study developed a human response criterion for wind turbine generators based on receptor received noise levels and termed it ‘Perception Detection Threshold.’ The study showed that the thresholds for wind turbine noise were below the thresholds of general tones. After validating the usefulness of the response function, the following annoyance table, based on an old ISO standard, now defunct,

was recommended to evaluate the community response. The annoyance table is presented in Table 4.1 below.

**Table 4.1 Estimated Community Response to Wind Turbine Generator Noise  
(From Reference 12 –Figure 12 of Reference 12, based on an ISO standard)**

Amount in dB by which the rated noise exceeds Threshold Level	Estimated Community Response	
	Category	Description
0	None	No Observed Reaction
5	Little	Sporadic Complaints
10	Medium	Widespread Complaints
15	Strong	Threats of Community Action
20	Very Strong	Vigorous Community Action

**NOTE:** **Rated Noise Level** – The actual noise level that would be measured at the receptor locations;

**Threshold Level** – The average ambient sound level that would exist in areas around the wind farm site.

A study, similar to that of Sheppard (Reference 12) is required to evaluate the detection threshold for modern wind turbines.

The annoyance study of Pedersen and Waye concluded that annoyance increases with sound levels. However, these annoyance studies have very small sample sizes and focussed on subjects living close to wind farms. No blind survey was conducted. Only 65 of the 356 respondents were exposed to noise levels of 37.5 dBA and above. The following categories – perception, dose-annoyance, sensitivity, attitude to source, visual exposure and rural setting – were included in the survey. The correlation between most of the categories and noise levels were small. The noise level and annoyance response was proportional to the exposure level. However, the sample size was too small. The subjects had prior exposure to wind turbines, making the sample biased. It must be acknowledged that the research of Pedersen and Waye has provided important insights into the human response of wind turbine noise and has considered important parameters.

However, the work of Pedersen and Waye need to be expanded to include large enough samples with unbiased subjects.

Finally, one of the arguments presented by anti-wind farm proponents is that ‘beating’ increases human annoyance. The only result that can be culled from the literature, Reference 18, is that the modulation frequencies, 0.5 to 1 Hz for wind turbines, are such that the wind turbine noise can be detected. Since major studies on wind turbine beating and human annoyance have not been conducted, major conclusions are not possible at this stage.

#### **4.5 SUMMARY**

Available literature on wind turbine noise was reviewed and the review focussed on four categories, considered important to the Ministry’s stated goals. The results of the review were presented in this section. The main findings of this section are:

- A) The local terrain conditions can influence meteorological conditions and can affect the expected noise output of the wind turbines;
- B) Assessment procedures applied in different jurisdictions are quite similar in their scope;
- C) Wind farm noise do not have significant low-frequency (infrasound) components;
- D) Further study needed in order to determine effect of modulation on human annoyance.

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## **5.0 REVIEW OF MOE'S NOISE POLICIES AS APPLIED TO WIND FARM NOISE**

The Ministry of the Environment released a guideline document, "Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators" in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. A summary of these interpretations by John Kowalewski was also published in the Canadian Acoustics Journal (Reference 33). The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits. These three documents are enclosed in Appendices A, B and C.

### **5.1 MOE'S ASSESSMENT PROCESS**

The assessment procedures of MOE are summarized below for completeness sake:

- I) All wind farm applications must obtain a Certificate of Approval from MOE. If individual wind turbines have a capacity of 2 MW or more, the project must undergo an Environmental assessment review;
- II) If there are no receptors within 1000 m of the wind farm boundary, no detailed noise assessment is necessary;
- III) The noise limits are established based on the location of the receptors in Class 1 & 2 areas and Class 3 areas.
- IV) The sound power levels of the wind turbines are to be obtained from the standard procedures contained in IEC Standard 61400-11, by applying the wind speeds at 10 m height above ground. [Reference 26].
- V) The sound pressure levels at each receptor location are to be evaluated applying the procedures of ISO 9613.

VI) The noise impact is assessed by comparing the predicted noise levels at individual receptor location with the noise limits established in Step III. The noise impact is evaluated at each wind speed over the operating range of the wind turbine specifications.

The noise limits are wind speed dependent and are summarized in Table 5.1 below.

**Table 5.1 Ontario Noise Assessment Limits**

<b>Wind Speed (m/s) @ 10 m height</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>
Wind Turbine Noise Criterion NPC-232 (dBA) (Rural) – Class 3 Areas	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA) (Urban) – Class 1 & 2 Areas	45	45	45	45	45	49	51	53

The MOE procedures outlined in Appendix A do not explicitly discuss the application of penalties for source character or apply particular meteorological conditions.

The MOE's assessment process is very similar to the procedures applied in the New Zealand (Reference R19), as it recognizes the usefulness of masking effects of ambient wind. The implicit assumption is that it is the ambient wind that generates the noise of wind turbines as well as background noise levels at receptor locations.

The Ministry's noise assessment guidelines for stationary sources of sound are based on the premise that noise from the stationary sources may be annoying when it is audible over and above the level of the so-called "ambient" or surrounding environmental "noise climate" at a particular location. However, audibility does not necessarily mean annoyance. Furthermore, annoyance is not the same for the entire population; people at the extreme of the statistical distribution may be annoyed at different noise levels. Such an approach was considered a 'sound' policy from the inception of the Model Municipal Noise Control by-Law issued by MOE in August 1978. The policies provide adequate protection from adverse noise pollution impacts as well as not imposing restrictive conditions on industrial noise sources. However, the MOE's

assessment, even though has provided a very simple procedure, has been very general in its overall scope. Two issues need to be resolved and are highlighted below.

## **5.2 PENALTY FOR SOURCE CHARACTER**

The guideline document that deals with noise assessment of wind turbines, enclosed in Appendix A, does not explicitly discuss penalties for characters such as tonal components of the wind turbine noise levels, even though reference to NPC-104 is included in the interpretation document. Further, the Ministry document, NPC-205 (enclosed in Appendix C) contains guidelines for penalties, which must be used if a particular wind turbine was found to contain tonal components. The implicit assumption is that the modern up-wind wind turbines have no dominant tones in their spectrum. It must be pointed out that most of the measurement results do show that the turbine noise spectrum is devoid of dominant tones. However, MOE needs to clarify and include source character adjustments in the main body of the interpretation document and even make references to the procedures contained in the IEC Standard (Reference 26) that are used to determine the presence of tones in the noise spectrum.

## **5.3 METEOROLOGICAL CONDITIONS**

One of the main arguments posed by van den Berg (Section 2) is that meteorological condition affect wind speed profiles with height and that the hub-height wind speed may be higher than predicted with the 10 m high wind speed being low. It was made clear in the review presented in Section 2 that the evidence presented to support these arguments were tenuous at best. However, the works of Botha (Reference 22) and Sondergaard (Reference 24) showed that local terrain conditions can dictate the wind profiles and the measurements of Reference 22 has shown that in flat terrains, the wind speed profile with height cannot be predicted accurately by standard methods such as the logarithmic shear function applied in Reference 26.

It is therefore, possible that, for a ‘worst-case scenario’, the hub-height velocities can be higher than expected thereby resulting in higher-than-expected noise levels with lower masking effect of the ambient wind at receptor locations. Some preliminary evaluations presented in Reference

32 showed that discrepancies of the order of 3 dBA are possible. Such a scenario needs to be accounted for in the Ministry's future updates of the assessment procedures. One example of a possible assessment procedure is described in Appendix F.

#### **5.4 SUMMARY**

The assessment procedures, currently, applied in the Province of Ontario by the Ministry of the Environment to evaluate wind farm noise levels were reviewed. The results showed that the procedures may have to be revised to incorporate additional factors. One possible assessment process is suggested Appendix F.



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## 6.0 CONCLUSIONS

As part of the review process of their assessment procedures, the Ministry of the Environment for the Province of Ontario has instituted a work project with different tasks. Four individual tasks were part of the review process.

The results of each of the tasks were presented in the previous sections. The conclusions for each of the tasks were included at the end of the relevant sections. The basic conclusions are summarized below:

- A) The research work undertaken by G. P. van den Berg didn't provide scientific evidence to support the few major hypotheses postulated concerning the wind turbine noise characteristics. However, the work of other researchers showed that local terrain conditions can impact the local meteorology and thereby the resulting noise levels;
- B) Assessment procedures applied in different jurisdictions showed the current Ministry of the Environment process is similar to other jurisdiction. Further, the MOE process has provided a balanced approach between noise impact and the need for wind farms, based on currently available scientific data.
- C) Literature review showed that additional research is still required to make definitive conclusions about wind turbine noise impacts as well as human response to wind farms. In addition, detailed research on meteorological conditions, and their impact on sound generation needs to be undertaken to realise definitive conclusions;
- D) The Ministry of the Environment's procedures to assess wind farm noise levels follow a simple procedure that is sound for most situations. However, additional concerns still need to be addressed in the next round of revisions to their assessment process. These revisions may need to be addressed after the results from future research provide scientifically consistent data for effects such as meteorology, human response and turbine noise source character.

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## **APPENDIX A**

### **INTERPRETATION FOR APPLYING MOE NPC TECHNICAL PUBLICATIONS TO WIND TURBINE GENERATORS**

## INTERPRETATION FOR APPLYING MOE NPC TECHNICAL PUBLICATIONS TO WIND TURBINE GENERATORS

Noise impacts of proposed wind turbine generators, i.e. wind turbines, are considered in the course of assessing an application for a Certificate of Approval (Air), in accordance with Section 9 of the Environmental Protection Act. The purpose of this guidance document is to assist proponents of wind turbine installations in determining what information should be submitted when applying for a Certificate of Approval (Air). It has been developed in order to provide consistency in the submissions and to streamline the review and approval process.

As a minimum, the information package must include details of the wind turbine design and operation, location of the wind turbine within the specific site and surrounding area as well as summary of compliance applicable to noise. The following defines a template for reports to be submitted to the MOE. This information is supplementary to the information in MOE Publication NPC-233, Information to be Submitted for Approval of Stationary Sources of Sound.

### REFERENCES

- [1] NPC-102 - Instrumentation
- [2] NPC-103 - Procedures
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- [5] NPC-206 - Sound Levels due to Road Traffic
- [6] NPC-232 - Sound Level Limits for Stationary Sources in Class 3 Areas (Rural)
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### TECHNICAL DEFINITIONS

#### "Class 1 Area"

means an area with an acoustical environment typical of a major population centre, where the background noise is dominated by the urban hum.

#### "Class 2 Area"

means an area with an acoustical environment that has qualities representative of both Class 1 and Class 3 Areas, and in which a low ambient sound level, normally occurring only between 23:00 and 07:00 hours in Class 1 Areas, will typically be realized as early as 19:00 hours.

Other characteristics which may indicate the presence of a Class 2 Area include:

- i. absence of urban hum between 19:00 and 23:00 hours;
- ii. evening background sound level defined by natural environment and infrequent human activity; and
- iii. no clearly audible sound from stationary sources other than from those under consideration.

### "Class 3 Area"

means a rural area with an acoustical environment that is dominated by natural sounds having little or no road traffic, such as the following:

- i. a small community with less than 1000 population;
- ii. agricultural area;
- iii. a rural recreational area such as a cottage or a resort area; or a wilderness area.

### Point of Reception

"Point of Reception" means any point on the premises of a person within 30 m of a dwelling or a camping area, where sound or vibration originating from other than those premises is received.

For the purpose of approval of new sources, including verifying compliance with Section 9 of the Act, the Point of Reception may be located on any of the following existing or zoned for future use premises: permanent or seasonal residences, hotels/motels, nursing/retirement homes, rental residences, hospitals, camp grounds, and noise sensitive buildings such as schools and places of worship.

For equipment/facilities proposed on premises such as nursing/retirement homes, rental residences, hospitals, and schools, the Point of Reception may be located on the same premises.

## **NOISE LIMITS**

The noise limits for a wind turbine or an array of such units (referred to as a "wind farm") are set relative to the existing MOE Noise Guidelines in NPC-205/NPC-232 as well as to the wind generated background noise. The proponents are required to demonstrate compliance with the following sound level limits:

### **Wind turbine installations in Class 1 & 2 Areas (Urban)**

#### **Wind speeds below 8 m/s**

The lowest sound level limit at a Point of Reception in Class 1 & 2 Areas (Urban), under conditions of average wind speed up to 8 m/s (29 km/h), expressed in terms of the hourly equivalent sound level (Leq) is 45 dBA or the minimum hourly background sound level established in accordance with requirements in Publications NPC-205/NPC-233, whichever is higher.

## Wind Turbine Installations in Class 3 Areas (Rural)

### Wind speeds below 6 m/s

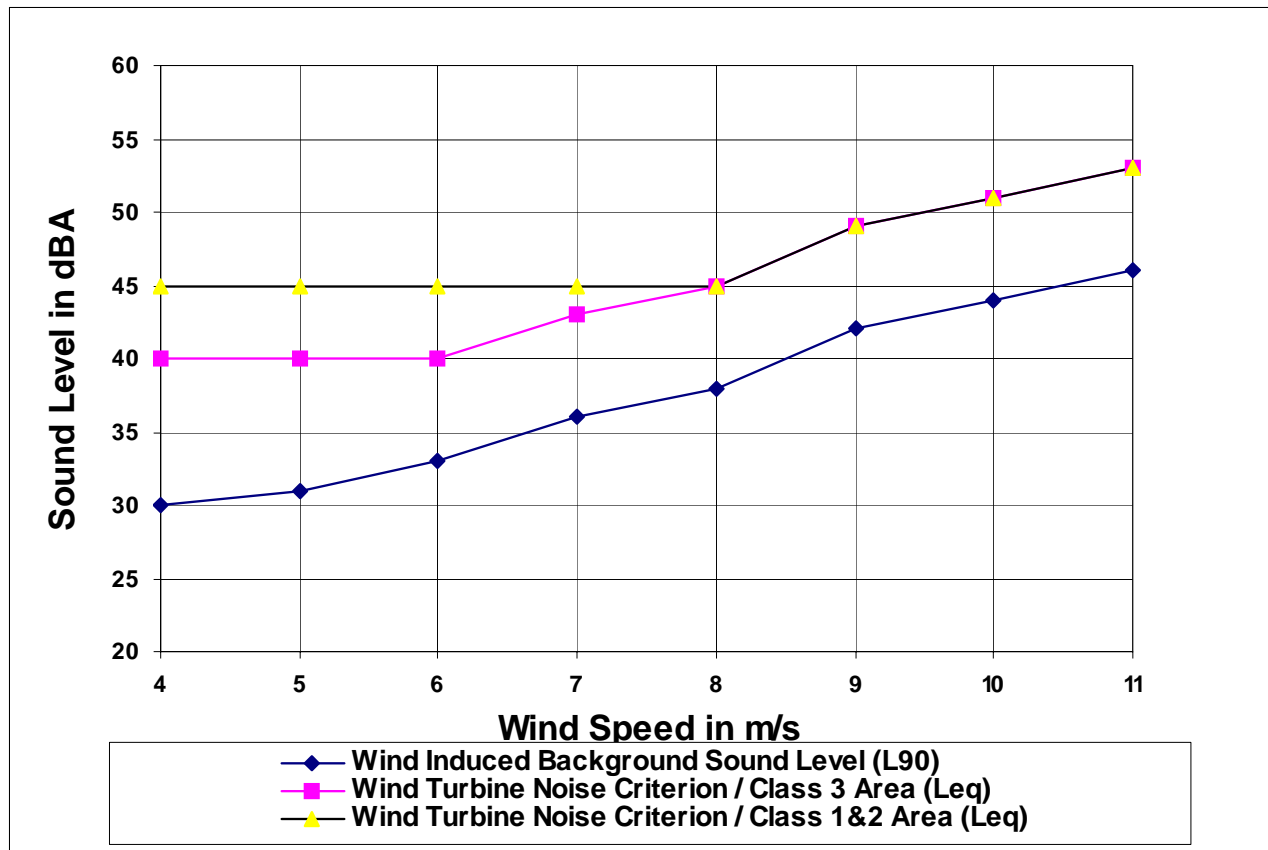
The lowest sound level limit at a Point of Reception in Class 3 Areas (Rural), under conditions of average wind speed up to 6 m/s (22 km/h), expressed in terms of the hourly equivalent energy sound level (Leq) is 40 dBA or the minimum hourly background sound level established in accordance with requirements in Publications NPC-232/NPC-233, whichever is higher.

## Wind Turbine Installations in Class 1& 2 and Class 3 Areas

### Wind speeds above 8 and 6 m/s respectively

The sound level limit at a Point of Reception in Class Areas 1 & 2 (Urban) or in Class 3 Areas (Rural), under conditions of average wind speed above 8 m/s and 6 m/s respectively, expressed in terms of the hourly equivalent energy sound level (Leq), is the wind induced background sound level, expressed in terms of ninetieth percentile sound level (L<sub>A90</sub>) plus 7 dB, or the minimum hourly background sound level established in accordance with requirements in Publications NPC-205/NPC-232/NPC-233, whichever is higher.

A summary of the above limits is shown in figure and table below.



Wind Speed (m/s)	4	5	6	7	8	9	10	11
Wind Turbine Noise Criterion NPC-232 (dBA)	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA)	45	45	45	45	45	49	51	53

## NOTE:

1. The measurement of wind induced background sound level is not required to establish the applicable criterion. The wind induced background sound level reference curve in the figure above was determined by correlating the ninetieth percentile sound level ( $L_{A90}$ ) with the average wind speed measured at a particularly quiet site.
2. If the existing minimum hourly background sound level, established in accordance with requirements in Publications NPC-205/NPC-232/NPC-233, is selected as the sound level limit, the measurement of wind speed (for the purpose of determination of wind induced background sound level) is not required. The selected limit applies in the entire range of wind speed under consideration from 4 m/s to 11 m/s with exception of the wind turbine noise criterion values higher than the existing minimum hourly background sound level.
3. Wind Turbine Noise Criterion at wind speeds expressed as fractional values of m/s should be interpolated from the above graph.

## REPORT CONTENTS AND FORMAT

The noise report must contain the required information, organized in a clear and concise manner. The report should include the following sections in the given sequence:

1. **Introduction**  
Objectives of report
2. **General Description of Wind Turbine Installation Site and Surrounds**  
Description of the site general environment, including: adjacent zoning, sensitive receiver locations (Points of Reception); suitable mapping of the site and surrounding area, providing elevations of source receivers and intervening structures or topography where applicable to the assessment;
3. **Description of Receptors**  
Detailed acoustical description of the area surrounding the facility including: Identification of the closest and/or the critical Points of Reception, identifying noise sensitive residential or institutional uses - (industrial, commercial uses are also desirable information); Determination of the applicable minimum hourly background sound level limit at the critical Points of Reception, in accordance with NPC 205/232 and NPC-233;
4. **Description of Sources**  
Description of the wind turbine (wind farm) including: manufacturer & model number; Design principle & geometric configuration (horizontal, vertical, upwind, downwind, rotor diameter and centre height, blade type, number of blades, tower height); Power train (direct from rotor to generator, indirect through gearbox); Operating details (single, twin or variable speed, power curve, generator rated power output and rotational speed); Park lay-out (for a wind farm);
5. **Wind Turbine Noise Emission Rating**  
Noise emission levels in terms of sound power level of the wind turbine as a function of wind speed (determined in accordance with IEC 61400-11 method), provided by the wind turbine manufacturer;

**6. Impact Assessment**

Calculation of the sound pressure level at each critical Point of Reception for each wind turbine or an aggregate of units (wind farm) using ISO 9613 method.

Noise impact assessment under a “worst case scenario” at the critical Points of Reception, up to a distance of 1000 m from the wind turbine (or closest unit in a wind farm); Impact assessment is not required for Points of Reception farther than 1000 m from the wind turbine (or closest unit in a wind farm);

Comparison with the applicable noise limit;

**7. Wind Turbine Summary Tables**

Wind Turbine Source Summary Table and Wind Turbine Assessment Summary Table; (samples attached);

**8. Conclusions and Recommendations**

Summary of impacts and verification of compliance with the noise limits;

**9. Appendices, etc.**

Details of measurements and calculations, specifications, plans, eng. dwgs, etc.

## **WIND TURBINE SUMMARY TABLES**

The noise report must contain Wind Turbine Summary Tables, summarising the results of the Acoustical Report and demonstrating compliance. The Wind Turbine Summary Tables must address pertinent source(s) and receptors (Points of Reception).

The information in the Wind Turbine Summary Tables must be presented in two tables:

1. Wind Turbine Source Summary Table
2. Wind Turbine Assessment Summary Table

The following examples of summary tables must be incorporated into the report:

**Wind Turbine Noise Emission Summary Table**  
(add rows for additional sources)

	Wind Turbine ID	Max PWL at wind speed <6 m/s	PWL at selected wind speed in m/s				
			7	8	9	10	11
1	WT6000	93	97	99	100	104	106
2							
3							

**Note:**

1. PWL denotes Sound Power Level in dB re  $10^{-12}$  Watt
2. Noise emissions of a wind farm are represented by a sum of PWL values for individual wind turbine units.

**Wind Turbine Noise Impact Assessment Summary Table**  
 Identify all receptors (add rows for additional Points of Reception)

Point of Reception ID	Receptor Description	Distance to closest Wind Turbine (m)	Sound Level Limit (dBA)														Compliance with Limit (Yes/No)
			Calculated Sound Pressure Level at Receptor (dBA) at selected Wind Speed in m/s											Applicable Background Sound Level			
			at selected Wind Speed in m/s											NPC 205	NPC 232		
6 or <	7	8	9	10	11	6 or <	7	8	9	10	11						
R1	Residence to East	100	43	44	<b>48</b>	<b>50</b>	<b>54</b>	<b>56</b>	45	45	45	49	51	53	46		No
R2	Apt. Bldg. to South	150	40	42	45	47	51	<b>53</b>	45	45	45	49	51	53	51		No
R3	Nursing Home to West	200	37	39	42	44	48	50	45	45	45	49	51	53	47		Yes
R4	Residence to North	260	35	38	40	42	46	48	40	43	45	49	51	53		44	Yes

**Note:** Values in the table which are **underlined/bold** denote an excess over the applicable limit.



## **APPENDIX B**

### **NPC - 232 - SOUND LEVEL LIMITS FOR STATIONARY SOURCES IN CLASS 3 AREAS (RURAL)**

**SOUND LEVEL LIMITS FOR  
STATIONARY SOURCES IN  
CLASS 3 AREAS (RURAL)**

**PUBLICATION NPC-232**

**OCTOBER 1995**



**Ministry  
of the  
Environment**

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ISBN 0-7778-4921-6  
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# Sound Level Limits for Stationary Sources in Class 3 Areas (Rural)

## Publication NPC-232

October 1995

*This Publication establishes sound level limits for stationary sources such as industrial and commercial establishments or ancillary transportation facilities, affecting points of reception in Class 3 Areas (Rural). It replaces Publication NPC-132 "Guidelines for Noise Control in Rural Areas" of the "Model Municipal Noise Control By-Law, Final Report, August 1978".*

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## 1. SCOPE

This Publication establishes sound level limits for stationary sources of sound such as industrial and commercial establishments or ancillary transportation facilities, affecting points of reception in Class 3 Areas (Rural). The limits apply to noise complaint investigations carried out in order to determine potential violation of Section 14 of the Environmental Protection Act. The limits also apply to the assessment of planned stationary sources of sound in compliance with Section 9 of the Environmental Protection Act, and under the provisions of the Aggregate Resources Act and the Environmental Assessment Act.

This Publication does not address sound and vibration produced by blasting; blasting in quarries and surface mines is considered in Reference [7].

The Publication includes an Annex, which provides additional details, definitions and rationale for the sound level limits.

## **2. REFERENCES**

Reference is made to the following publications:

- [1] NPC-101 - Technical Definitions
- [2] NPC-102 - Instrumentation
- [3] NPC-103 - Procedures
- [4] NPC-104 - Sound Level Adjustments
- [5] NPC-205 - Sound Level Limits for Stationary Sources in Class 1 & 2 Areas (Urban)
- [6] NPC-206 - Sound Levels due to Road Traffic
- [7] NPC-119 - Blasting
- [8] NPC-216 - Residential Air Conditioning Devices
- [10] NPC-233 - Information to be Submitted for Approval of Stationary Sources of Sound
- [12] ORNAMENT, Ontario Road Noise Analysis Method for Environment and Transportation, Technical Document, Ontario Ministry of the Environment, ISBN 0-7729-6376, 1989

References [1] to [4] and [7] can be found in the  
Model Municipal Noise Control By-Law, Ontario Ministry of the Environment, Final Report, August 1978.

## **2. DEFINITIONS**

"Ambient sound level"  
means Background sound level.

"Background sound level"  
is the sound level that is present in the environment, produced by noise sources other than the source under impact assessment. Highly intrusive short duration noise caused by a source such as an aircraft fly-over or a train pass-by is excluded from the determination of the background sound level.

"Class 1 Area"  
means an area with an acoustical environment typical of a major population centre, where the background noise is dominated by the urban hum.

**"Class 2 Area"**

means an area with an acoustical environment that has qualities representative of both Class 1 and Class 3 Areas, and in which a low ambient sound level, normally occurring only between 23:00 and 07:00 hours in Class 1 Areas, will typically be realized as early as 19:00 hours.

Other characteristics which may indicate the presence of a Class 2 Area include:

- absence of urban hum between 19:00 and 23:00 hours;
- evening background sound level defined by natural environment and infrequent human activity; and
- no clearly audible sound from stationary sources other than from those under impact assessment.

**"Class 3 Area"**

means a rural area with an acoustical environment that is dominated by natural sounds having little or no road traffic, such as the following:

- a small community with less than 1000 population;
- agricultural area;
- a rural recreational area such as a cottage or a resort area; or
- a wilderness area.

Other technical terms are defined in Reference [1] and in the Annex to Publication NPC-232.

**3. ESTABLISHMENT OF LIMITS - OBJECTIVE**

The sound level limit at a point of reception must be established based on the principle of "predictable worst case" noise impact. In general, the limit is given by the background sound level at the point of reception. The sound level limit must represent the minimum background sound level that occurs or is likely to occur during the operation of the stationary source under impact assessment.

**4. BACKGROUND SOUND LEVELS OF THE NATURAL ENVIRONMENT**

The One Hour Equivalent Sound Level ( $L_{eq}$ ) and/or the One Hour Ninetieth Percentile Sound Level ( $L_{90}$ ) of the natural environment shall be obtained by measurement performed in accordance with Section 7. The results of the measurements must not be affected by the sound of the stationary source under impact assessment.

The time interval between the background sound level measurement and the measurement of the sound level produced by the stationary source under impact assessment should be minimized as much as possible. Preferably, the two measurements should be carried out within one hour of each other.

**5. SOUND LEVELS DUE TO STATIONARY SOURCES****(1) Complaint Investigation of Stationary Sources**

The One Hour Equivalent Sound Level ( $L_{eq}$ ) and/or the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) produced by the stationary sources shall be obtained by measurement performed in accordance with Section 7.

**(2) Approval of Stationary Sources**

The One Hour Equivalent Sound Level ( $L_{eq}$ ) and/or the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) produced by the stationary sources shall be obtained by measurement or prediction. The estimation of the  $L_{eq}$  and/or  $L_{LM}$  of the stationary source under impact assessment shall reflect the principle of "predictable worst case" noise impact. The "predictable worst case" noise impact occurs during the hour when the difference between the predicted sound level produced by the stationary source and the background sound level of the natural environment is at a maximum.

**6. PROCEDURES**

All sound level measurements of the One Hour Equivalent Sound Level ( $L_{eq}$ ) and the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) shall be made in accordance with Reference [3].

All sound level measurements of the One Hour Ninetieth Percentile Sound Level ( $L_{90}$ ) shall be made using a Sound Level Meter capable of measuring percentile sound levels. The meter shall meet the applicable requirements for an Integrating Sound Level Meter of Reference [2]. The measurements shall be carried out following procedures for the measurement of varying sound described in Reference [3].

Sound from existing adjacent stationary sources may be included in the determination of the background hourly sound levels  $L_{eq}$  and  $L_{90}$ , if such stationary sources are not under consideration for noise abatement by the Municipality or the Ministry of Environment and Energy.

**7. SOUND LEVEL LIMITS - GENERAL**

(1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ), is the lower of:

- the background One Hour Equivalent Sound Level ( $L_{eq}$ ) obtained pursuant to Section 5; and
- the background One Hour Ninetieth Percentile Sound Level ( $L_{90}$ ) plus 15 dB, i.e.  $L_{90} + 15$  dB, obtained pursuant to Section 5.

(2) For sound from a stationary source, including Quasi-Steady Impulsive Sound but not including other impulsive sound, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the One Hour Equivalent Sound Level ( $L_{eq}$ ), is the lower of:

- the background One Hour Equivalent Sound Level ( $L_{eq}$ ) obtained pursuant to Section 5; and
- the background One Hour Ninetieth Percentile Sound Level ( $L_{90}$ ) plus 10 dB, i.e.  $L_{90} + 10$  dB, obtained pursuant to Section 5.

**8. SOUND LEVEL LIMITS - SPECIFIC IMPULSIVE SOUNDS**

(1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is an industrial metal working operation (including but not limited to forging, hammering, punching, stamping, cutting, forming and moulding), the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ), is 60 dBAI, if the stationary source were operating before January 1, 1980, and otherwise is 50 dBAI.

(2) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is the discharge of firearms on the premises of a licensed gun club, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ), is:

- 70 dBAI if the gun club were operating before January 1, 1980; or
- 50 dBAI if the gun club began to operate after January 1, 1980; or
- the  $L_{LM}$  prior to expansion, alteration or conversion.

- (3) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is not a blasting operation in a surface mine or quarry, characterized by impulses which are so infrequent that they cannot normally be measured using the procedure for frequent impulses of Reference [3], the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the impulse sound level, is 100 dBAI.

## 9. SOUND LEVEL LIMITS - PEST CONTROL DEVICES

- (1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a pest control device employed solely to protect growing crops, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ), is 70 dBAI.
- (2) For sound, including Quasi-Steady Impulsive Sound but not including other impulsive sound, from a pest control device employed solely to protect growing crops, the sound level limit at a point of reception within 30 m of a dwelling or a camping area, expressed in terms of the One Hour Equivalent Sound Level ( $L_{eq}$ ), is 60 dBA.

## 10. PROHIBITION - PEST CONTROL DEVICES

The operation of a pest control device employed solely to protect growing crops is prohibited during the hours of darkness, sunset to sunrise.

## 11. PRE-EMPTION

The least restrictive sound level limit of Sections 8, 9 and 10 applies.

## 12. EXCLUSION

No restrictions apply to any stationary source resulting in a One Hour Equivalent Sound Level ( $L_{eq}$ ) or a Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ), at a point of reception within 30 m of a dwelling or a camping area, lower than the minimum values for that time period, as specified in Table 232-1.

**TABLE 232-1**  
**Minimum Values of One Hour  $L_{eq}$  or  $L_{LM}$  by Time of Day**

Time of Day	One Hour $L_{eq}$ (dBA) or $L_{LM}$ (dBAI)
0700 - 1900	45
1900 - 2300	40
2300 - 0700	40





## Annex to Publication NPC-232 Sound Level Limits for Stationary Sources in Class 3 Areas (Rural)

October 1995

### A.1. GENERAL

The definitions in Publication NPC-232 of a Class 3 Area (Rural), as well as Class 1 and 2 Areas (Urban), provide a broad characterization of the areas including a range of localities. In formulating the definitions, consideration was given to the fact that the terms "rural" and "urban" embody a conception of distinct types of dwelling habitat.

On one hand, the term "urban" traditionally conveys a distinct image of a concentration of people and activities in a predominantly man-made environment dominated by road traffic noise, making intensive use of the space available. On the other hand, the term "rural" brings to mind a sparse distribution of people and activities in a predominantly natural environment using land extensively (farming) or not at all (wilderness areas). In between these two categories fall areas that exhibit characteristics of both "urban" and "rural" areas, particularly at different times of the day.

It is, however, evident that not all of the environment will fit neatly into one of these categories. The predominance of road traffic in the area is a significant factor in determining rurality. For example, a residential property in an isolated recreational area, but close to a major roadway, would not be considered to be located in a Class 3 Area.

While examples of a rural setting, described in Publication NPC-232 provide some general guidelines, any classification of a point of reception as being in a Class 1, 2 or 3 Area should be made on an individual basis. The classification can, and should, utilize normally available information on zoning by-laws, official plans, and other policy statements, as well as the future character of the particular piece of land in question and the land in its vicinity.

The standard of environmental noise acceptability for a stationary source is, in general, expressed as the difference between the noise from the source and the background noise. In rural areas, this background noise is formed by natural sounds rather than man-made sounds.

The background noise may also include contributions from existing stationary sources adjacent to the stationary source under impact assessment. Contributions of these secondary stationary noise sources are considered to be a part of the existing noise environment, and may be included in the measurement of the background sound levels, provided that they are not under consideration for noise abatement by the Municipality or the Ministry of Environment and Energy.

In Class 1 and 2 Areas where the acoustical environment is governed primarily by road traffic, the background noise is best described by the energy equivalent sound level ( $L_{eq}$ ). However, the background noise in Class 3 Areas is often better described in terms of the ninetieth percentile sound level ( $L_{90}$ ). Therefore, Publication NPC-232 has established both the  $L_{90}$  as well as the  $L_{eq}$  of the background as the limits against which the intrusion of the source, measured in terms of the  $L_{eq}$ , is assessed.

### A.2. APPLICATION

Sound level limits contained in this Publication do not apply to non-stationary noise sources nor to any equipment, apparatus or device used in agriculture for food crop seeding, chemical spraying or harvesting. In addition, several specific noise sources have been addressed in separate Publications. Limits for residential air conditioners are contained in Publication NPC-216 - Residential Air Conditioning Devices, Reference [8], and the limits for blasting operations in quarries and surface mines are contained in Publication NPC-119 - Blasting, Reference [7].

**A.3. STATIONARY SOURCES**

The objective of the definition of a stationary source of sound is to address sources such as industrial and commercial establishments or ancillary transportation facilities. In order to further clarify the scope of the definition, the following list identifies examples of installations, equipment, activities or facilities that are included and those that are excluded as stationary sources.

**(1) Included Sources**

Individual stationary sources such as:

- Heating, ventilating and air conditioning (HVAC) equipment;
- Rotating machinery;
- Impacting mechanical sources;
- Generators;
- Burners;
- Grain dryers.

Facilities, usually comprising many sources of sound. In this case, the stationary source is understood to encompass all the activities taking place within the property boundary of the facility. The following are examples of such facilities:

- Industrial facilities;
- Commercial facilities;
- Ancillary transportation facilities;
- Aggregate extraction facilities;
- Warehousing facilities;
- Maintenance and repair facilities;
- Snow disposal sites;
- Routine loading and unloading facilities (supermarkets, assembly plants, etc.).

Other sources such as:

- Car washes;
- Race tracks;
- Firearm Ranges.

**(2) Excluded Sources**

Specific sources or facilities:

- Construction activities;
- Transportation corridors, i.e. roadways and railways;
- Residential air conditioning devices including air conditioners and heat pumps;
- Gas stations;
- Auditory warning devices required or authorized by law or in accordance with good safety practices;
- Occasional movement of vehicles on the property such as infrequent delivery of goods to convenience stores, fast food restaurants, etc.

Other noise sources, normally addressed in a qualitative manner in municipal noise by-laws:

- The operation of auditory signalling devices, including but not limited to the ringing of bells or gongs and the blowing of horns or sirens or whistles, or the production, reproduction or amplification of any similar sounds by electronic means;
- Noise produced by animals kept as domestic pets such as dogs barking;
- Tools and devices used by occupants for domestic purposes such as domestic power tools, radios and televisions, etc., or activities associated with domestic situations such as domestic quarrels, noisy parties, etc;

Noise resulting from gathering of people at facilities such as restaurants and parks.

Activities related to essential service and maintenance of public facilities such as but not limited to roadways, parks and sewers, including snow removal, road cleaning, road repair and maintenance, lawn mowing and maintenance, sewage removal, garbage collection, etc.

#### **A.4. PREDICTABLE WORST CASE IMPACT**

The assessment of noise impact requires the determination of the "predictable worst case" impact. The "predictable worst case" impact assessment should establish the largest noise excess produced by the source over the applicable limit. The assessment should reflect a planned and predictable mode of operation of the stationary source.

It is important to emphasize that the "predictable worst case" impact does not necessarily mean that the sound level of the source is highest; it means that the excess over the limit is largest. For example, the excess over the applicable limit at night may be larger even if the day-time sound level produced by the source is higher.

#### **A.5. DEFINITIONS**

In the interpretation of Publication NPC-232, the following definitions are of particular relevance:

- Ancillary Transportation Facilities  
"Ancillary transportation facilities" mean subsidiary locations where operations and activities associated with the housing of transportation equipment (or personnel) take place. Examples of ancillary transportation facilities include, but are not limited to, substations, vehicle storage and maintenance facilities, fans, fan and vent shafts, mechanical equipment plants, emergency services buildings, etc;
- Construction  
"Construction" includes erection, alteration, repair, dismantling, demolition, structural maintenance, painting, moving, land clearing, earth moving, grading, excavating, the laying of pipe and conduit whether above or below ground level, street and highway building, concreting, equipment installation and alteration and the structural installation of construction components and materials in any form or for any purpose, and includes any work in connection therewith; "construction" excludes activities associated with the operation at waste and snow disposal sites;
- Construction Equipment  
"Construction equipment" means any equipment or device designed and intended for use in construction, or material handling including but not limited to, air compressors, pile drivers, pneumatic or hydraulic tools, bulldozers, tractors, excavators, trenchers, cranes, derricks, loaders, scrapers, pavers, generators, off-highway haulers or trucks, ditchers, compactors and rollers, pumps, concrete mixers, graders, or other material handling equipment;
- Conveyance  
"Conveyance" includes a vehicle and any other device employed to transport a person or persons or goods from place to place but does not include any such device or vehicle if operated only within the premises of a person;
- Highway  
"Highway" includes a common and public highway, street, avenue, parkway, driveway, square, place, bridge, viaduct or trestle designed and intended for, or used by, the general public for the passage of vehicles;

- Motor Vehicle  
"Motor vehicle" includes an automobile, motorcycle, and any other vehicle propelled or driven otherwise than by muscular power, but does not include the cars of diesel, electric or steam railways, or other motor vehicles running only upon rails, or a motorized snow vehicle, traction engine, farm tractor, self-propelled implement of husbandry or road-building machine within the meaning of the Highway Traffic Act;
- Motorized Conveyance  
"Motorized conveyance" means a conveyance propelled or driven otherwise than by muscular, gravitational or wind power;
- Noise  
"Noise" means unwanted sound;
- Point of Reception - Class 3 Area  
"Point of reception - Class 3 Area" means a point on the premises of a person within 30 m of a dwelling or a camping area, where sound or vibration originating from other than those premises is received.  
  
For the purpose of approval of new sources, including verifying compliance with Section 9 of the Environmental Protection Act, the point of reception may be located on any of the following existing or zoned for future use premises: permanent or seasonal residences, hotels/motels, nursing/retirement homes, rental residences, hospitals, camp grounds, and noise sensitive buildings such as schools and places of worship.  
  
For equipment/facilities proposed on premises such as nursing/retirement homes, rental residences, hospitals, and schools, the point of reception may be located on the same premises;
- Stationary Source  
"Stationary source" means a source of sound which does not normally move from place to place and includes the premises of a person as one stationary source, unless the dominant source of sound on those premises is construction or a conveyance;
- Urban Hum  
means aggregate sound of many unidentifiable, mostly road traffic related noise sources.

## **APPENDIX C**

### **NPC - 205 - SOUND LEVEL LIMITS FOR STATIONARY SOURCES IN CLASS 1 & 2 AREAS (URBAN)**

**SOUND LEVEL LIMITS FOR  
STATIONARY SOURCES IN  
CLASS 1 & 2 AREAS (URBAN)**

**PUBLICATION NPC-205**

**OCTOBER 1995**



**Ministry  
of the  
Environment**

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# Sound Level Limits for Stationary Sources in Class 1 & 2 Areas (Urban) Publication NPC-205

October 1995

*This Publication establishes sound level limits for stationary sources such as industrial and commercial establishments or ancillary transportation facilities, affecting points of reception in Class 1 and 2 Areas (Urban). It replaces Publication NPC-105 "Stationary Sources" of the "Model Municipal Noise Control By-Law, Final Report, August 1978".*

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### 1. SCOPE

This Publication establishes sound level limits for stationary sources such as industrial and commercial establishments or ancillary transportation facilities, affecting points of reception in Class 1 and 2 Areas (Urban). The limits apply to noise complaint investigations carried out in order to determine potential violation of Section 14 of the Environmental Protection Act. The limits also apply to the assessment of planned stationary sources of sound in compliance with Section 9 of the Environmental Protection Act, and under the provisions of the Aggregate Resources Act and the Environmental Assessment Act.

This Publication does not address sound and vibration produced by blasting; blasting in quarries and surface mines is considered in Reference [7].

The Publication includes an Annex, which provides additional details, definitions and rationale for the sound level limits.

## **2. REFERENCES**

Reference is made to the following publications:

- [1] NPC-101 - Technical Definitions
- [2] NPC-102 - Instrumentation
- [3] NPC-103 - Procedures
- [4] NPC-104 - Sound Level Adjustments
- [6] NPC-206 - Sound Levels due to Road Traffic
- [7] NPC-119 - Blasting
- [8] NPC-216 - Residential Air Conditioning Devices
- [9] NPC-232 - Sound Level Limits for Stationary Sources in Class 3 Areas (Rural)
- [10] NPC-233 - Information to be Submitted for Approval of Stationary Sources of Sound
- [12] ORNAMENT, Ontario Road Noise Analysis Method for Environment and Transportation, Technical Document, Ontario Ministry of the Environment, ISBN 0-7729-6376, 1989

References [1] to [4] and [7] can be found in the  
Model Municipal Noise Control By-Law, Ontario Ministry of the Environment, Final Report, August 1978.

## **3. TECHNICAL DEFINITIONS**

"Ambient sound level"  
means Background sound level.

"Background sound level"  
is the sound level that is present in the environment, produced by noise sources other than the source under impact assessment. Highly intrusive short duration noise caused by a source such as an aircraft fly-over or a train pass-by is excluded from the determination of the background sound level.

"Class 1 Area"  
means an area with an acoustical environment typical of a major population centre, where the background noise is dominated by the urban hum.

**"Class 2 Area"**

means an area with an acoustical environment that has qualities representative of both Class 1 and Class 3 Areas, and in which a low ambient sound level, normally occurring only between 23:00 and 07:00 hours in Class 1 Areas, will typically be realized as early as 19:00 hours.

Other characteristics which may indicate the presence of a Class 2 Area include:

- absence of urban hum between 19:00 and 23:00 hours;
- evening background sound level defined by natural environment and infrequent human activity; and
- no clearly audible sound from stationary sources other than from those under impact assessment.

**"Class 3 Area"**

means a rural area with an acoustical environment that is dominated by natural sounds having little or no road traffic, such as the following:

- a small community with less than 1000 population;
- agricultural area;
- a rural recreational area such as a cottage or a resort area; or
- a wilderness area.

Other technical terms are defined in Reference [1] and in the Annex to Publication NPC-205.

**4. ESTABLISHMENT OF LIMITS - OBJECTIVE**

The sound level limit at a point of reception must be established based on the principle of "predictable worst case" noise impact. In general, the limit is given by the background sound level at the point of reception. The sound level limit must represent the minimum background sound level that occurs or is likely to occur during the operation of the stationary source under impact assessment.

**5. BACKGROUND SOUND LEVELS**

The time interval between the background sound level measurement and the measurement of the sound level produced by the stationary source under impact assessment should be minimized as much as possible. Preferably, the two measurements should be carried out within one hour of each other.

**6. SOUND LEVELS DUE TO STATIONARY SOURCES****(1) Complaint Investigation of Stationary Sources**

The One Hour Equivalent Sound Level ( $L_{eq}$ ) and/or the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) produced by the stationary sources shall be obtained by measurement performed in accordance with Section 7.

**(2) Approval of Stationary Sources**

The One Hour Equivalent Sound Level ( $L_{eq}$ ) and/or the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) produced by the stationary sources shall be obtained by measurement or prediction. The estimation of the  $L_{eq}$  and/or  $L_{LM}$  of the stationary source under impact assessment shall reflect the principle of "predictable worst case" noise impact. The "predictable worst case" noise impact occurs during the hour when the difference between the predicted sound level produced by the stationary source and the background sound level of the natural environment is at a maximum.

**7. PROCEDURES**

All sound level measurements and calculations shall be made in accordance with References [3], [6] and [12].

Sound from existing adjacent stationary sources may be included in the determination of the background One Hour Equivalent Sound Level ( $L_{eq}$ ) if such stationary sources of sound are not under consideration for noise abatement by the Municipality or the Ministry of Environment and Energy.

**8. SOUND LEVEL LIMITS - GENERAL**

- (1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source, the sound level limit expressed in terms of the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) is the background One Hour Equivalent Sound Level ( $L_{eq}$ ) typically caused by road traffic as obtained pursuant to Section 6 for that point of reception.
- (2) For sound from a stationary source, including Quasi-Steady Impulsive Sound but not including other impulsive sound, the sound level limit expressed in terms of the One Hour Equivalent Sound Level ( $L_{eq}$ ) is the background One Hour Equivalent Sound Level ( $L_{eq}$ ) typically caused by road traffic as obtained pursuant to Section 6 for that point of reception.

**9. SOUND LEVEL LIMITS - SPECIFIC IMPULSIVE SOUNDS**

- (1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is an industrial metal working operation (including but not limited to forging, hammering, punching, stamping, cutting, forming and moulding), the sound level limit at a point of reception expressed in terms of the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) is 60 dBAI, if the stationary source were operating before January 1, 1980, and otherwise is 50 dBAI.
- (2) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is the discharge of firearms on the premises of a licensed gun club, the sound level limit at a point of reception expressed in terms of the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) is:
  - 70 dBAI if the gun club were operating before January 1, 1980; or
  - 50 dBAI if the gun club began to operate after January 1, 1980; or
  - the  $L_{LM}$  prior to expansion, alteration or conversion.
- (3) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a stationary source which is not a blasting operation in a surface mine or quarry, characterized by impulses which are so infrequent that they cannot normally be measured using the procedure for frequent impulses of Reference [3] the sound level limit at a point of reception expressed in terms of the impulse sound level is 100 dBAI.

**10. SOUND LEVEL LIMITS - PEST CONTROL DEVICES**

- (1) For impulsive sound, other than Quasi-Steady Impulsive Sound, from a pest control device employed solely to protect growing crops, the sound level limit at a point of reception expressed in terms of the Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) is 70 dBAI.
- (2) For sound, including Quasi-Steady Impulsive Sound but not including other impulsive sound, from a pest control device employed solely to protect growing crops, the sound level limit at a point of reception expressed in terms of the One Hour Equivalent Sound Level ( $L_{eq}$ ) is 60 dBA.

**11. PROHIBITION - PEST CONTROL DEVICES**

The operation of a pest control device employed solely to protect growing crops outdoors during the hours of darkness, sunset to sunrise, is prohibited.

**12. PRE-EMPTION**

The least restrictive sound level limit of Sections 8, 9 and 10 applies.

**13. EXCLUSION**

No restrictions apply to a stationary source resulting in a One Hour Equivalent Sound Level ( $L_{eq}$ ) or a Logarithmic Mean Impulse Sound Level ( $L_{LM}$ ) lower than the minimum values for that time period specified in Table 205-1.

**TABLE 205-1**
**Minimum Values of One Hour  $L_{eq}$  or  $L_{LM}$  by Time of Day**

Time of Day	One Hour $L_{eq}$ (dBA) or $L_{LM}$ (dBAI)	
	Class 1 Area	Class 2 Area
0700 - 1900	50	50
1900 - 2300	47	45
2300 - 0700	45	45



## **Annex to Publication NPC-205**

### **Sound Level Limits for Stationary Sources in Class 1 & 2 Areas (Urban)**

October 1995

#### **A.1. GENERAL**

In general, noises are annoying because they are heard over and above the level of the so-called "background" or surrounding environmental noise climate at a particular location. The standard for environmental noise acceptability of stationary sources is therefore expressed as the difference between noise from the source and the background noise.

The background noise is essentially made up of the road traffic noise which creates an "urban hum". It may also include contributions from existing industry or commercial activity adjacent to the stationary source under investigation. Contributions of these secondary noise sources are considered to be a part of urban hum and may be included in the measurements or calculation of the background sound levels, provided that they are not under consideration for noise abatement by the Municipality or the Ministry of Environment and Energy.

The sound level limits specified in Section 8 of Publication NPC-205 represent the general limitation on noise produced by stationary sources. Some noises, however, are annoying no matter where or in what kind of environment they exist. High level impulsive noises represent a special category and, consequently, are restricted by an absolute limitation. Sections 9 and 10 of this Publication provide criteria of acceptability for specific impulsive noise sources.

#### **A.2. APPLICATION**

The limits presented in Publication NPC-205 are designed for the control of noise from sources located in industrial, commercial or residential areas. The limits apply to points of reception located in Class 1 and Class 2 Areas.

Sound level limits contained in Publication NPC-205 do not apply to the excluded noise sources listed in Section A.3.(2) and neither do they apply to any equipment, apparatus or device used in agriculture for food crop seeding, chemical spraying or harvesting. In addition, several specific noise sources have been addressed in separate Publications. Limits for residential air conditioners are contained in Publication NPC-216 - Residential Air Conditioning Devices, Reference [8] and the limits for blasting operations in quarries and surface mines are contained in Publication NPC-119 - Blasting, Reference [7].

#### **A.3. STATIONARY SOURCES**

The objective of the definition of a stationary source of sound is to address sources such as industrial and commercial establishments or ancillary transportation facilities. In order to further clarify the scope of the definition, the following list identifies examples of installations, equipment, activities or facilities that are included and those that are excluded as stationary sources.

##### **(1) Included Sources**

Individual stationary sources such as:

- Heating, ventilating and air conditioning (HVAC) equipment;
- Rotating machinery;
- Impacting mechanical sources;
- Generators;
- Burners;
- Grain dryers.

Facilities, usually comprising many sources of sound. In this case, the stationary source is understood to encompass all the activities taking place within the property boundary of the facility. The following are examples of such facilities:

- Industrial facilities;
- Commercial facilities;
- Ancillary transportation facilities;
- Aggregate extraction facilities;
- Warehousing facilities;
- Maintenance and repair facilities;
- Snow disposal sites;
- Routine loading and unloading facilities (supermarkets, assembly plants, etc.).

Other sources such as:

- Car washes;
- Race tracks;
- Firearm Ranges.

## **(2) Excluded Sources**

Specific sources or facilities:

- Construction activities;
- Transportation corridors, i.e. roadways and railways;
- Residential air conditioning devices including air conditioners and heat pumps;
- Gas stations;
- Auditory warning devices required or authorized by law or in accordance with good safety practices;
- Occasional movement of vehicles on the property such as infrequent delivery of goods to convenience stores, fast food restaurants, etc.

Other noise sources, normally addressed in a qualitative manner in municipal noise by-laws:

- The operation of auditory signalling devices, including but not limited to the ringing of bells or gongs and the blowing of horns or sirens or whistles, or the production, reproduction or amplification of any similar sounds by electronic means;
- Noise produced by animals kept as domestic pets such as dogs barking;
- Tools and devices used by occupants for domestic purposes such as domestic power tools, radios and televisions, etc., or activities associated with domestic situations such as domestic quarrels, noisy parties, etc.;
- Noise resulting from gathering of people at facilities such as restaurants and parks.

Activities related to essential service and maintenance of public facilities such as but not limited to roadways, parks and sewers, including snow removal, road cleaning, road repair and maintenance, lawn mowing and maintenance, sewage removal, garbage collection, etc.

### **A.4. PREDICTABLE WORST CASE IMPACT**

The assessment of noise impact requires the determination of the "predictable worst case" impact. The "predictable worst case" impact assessment should establish the largest noise excess produced by the source over the applicable limit. The assessment should reflect a planned and predictable mode of operation of the stationary source.

It is important to emphasize that the "predictable worst case" impact does not necessarily mean that the sound level of the source is highest; it means that the excess over the limit is largest. For example, the excess over the applicable limit at night may be larger even if the day-time sound level produced by the source is higher.



**A.5. DEFINITIONS**

In the interpretation of Publication NPC-205, the following definitions are of particular relevance:

- Ancillary Transportation Facilities  
"Ancillary transportation facilities" mean subsidiary locations where operations and activities associated with the housing of transportation equipment (or personnel) take place. Examples of ancillary transportation facilities include, but are not limited to, substations, vehicle storage and maintenance facilities, fans, fan and vent shafts, mechanical equipment plants, emergency services buildings, etc;
- Construction  
"Construction" includes erection, alteration, repair, dismantling, demolition, structural maintenance, painting, moving, land clearing, earth moving, grading, excavating, the laying of pipe and conduit whether above or below ground level, street and highway building, concreting, equipment installation and alteration and the structural installation of construction components and materials in any form or for any purpose, and includes any work in connection therewith; "construction" excludes activities associated with the operation at waste and snow disposal sites;
- Construction Equipment  
"Construction equipment" means any equipment or device designed and intended for use in construction, or material handling including but not limited to, air compressors, pile drivers, pneumatic or hydraulic tools, bulldozers, tractors, excavators, trenchers, cranes, derricks, loaders, scrapers, pavers, generators, off-highway haulers or trucks, ditchers, compactors and rollers, pumps, concrete mixers, graders, or other material handling equipment;
- Conveyance  
"Conveyance" includes a vehicle and any other device employed to transport a person or persons or goods from place to place but does not include any such device or vehicle if operated only within the premises of a person;
- Highway  
"Highway" includes a common and public highway, street, avenue, parkway, driveway, square, place, bridge, viaduct or trestle designed and intended for, or used by, the general public for the passage of vehicles;
- Motor Vehicle  
"Motor vehicle" includes an automobile, motorcycle, and any other vehicle propelled or driven otherwise than by muscular power, but does not include the cars of diesel, electric or steam railways, or other motor vehicles running only upon rails, or a motorized snow vehicle, traction engine, farm tractor, self-propelled implement of husbandry or road-building machine within the meaning of the Highway Traffic Act;
- Motorized Conveyance  
"Motorized conveyance" means a conveyance propelled or driven otherwise than by muscular, gravitational or wind power;
- Noise  
"Noise" means unwanted sound;
- Point of Reception  
"Point of reception" means any point on the premises of a person where sound or vibration originating from other than those premises is received.

For the purpose of approval of new sources, including verifying compliance with Section 9 of the Environmental Protection Act, the point of reception may be located on any of the following existing or zoned for future use premises: permanent or seasonal residences, hotels/motels, nursing/retirement homes, rental residences, hospitals, camp grounds, and noise sensitive buildings such as schools and places of worship.

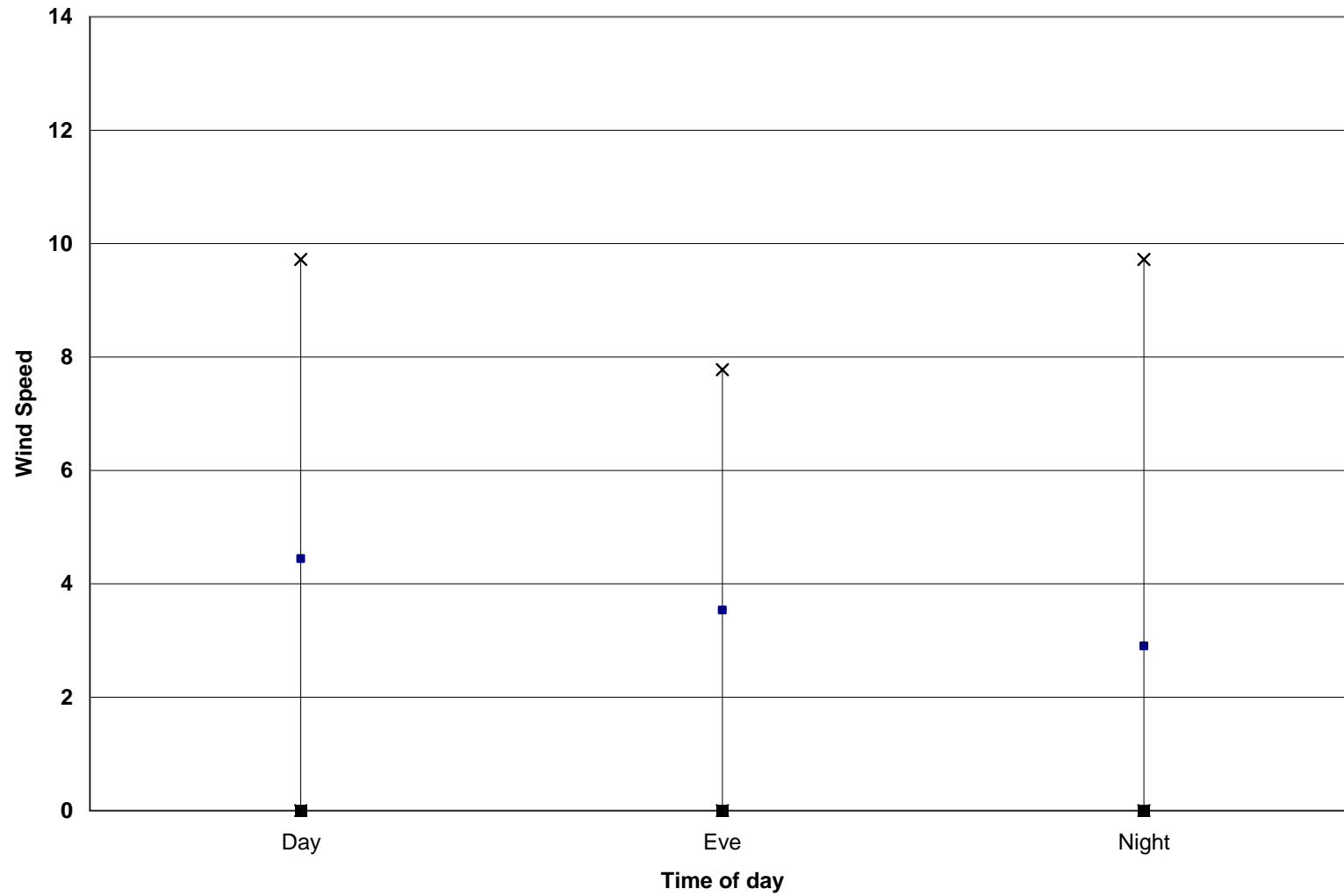
For equipment/facilities proposed on premises such as nursing/retirement homes, rental residences, hospitals, and schools, the point of reception may be located on the same premises;

- Stationary Source  
"Stationary source" means a source of sound which does not normally move from place to place and includes the premises of a person as one stationary source, unless the dominant source of sound on those premises is construction or a conveyance;
- Urban Hum  
means aggregate sound of many unidentifiable, mostly road traffic related noise sources.

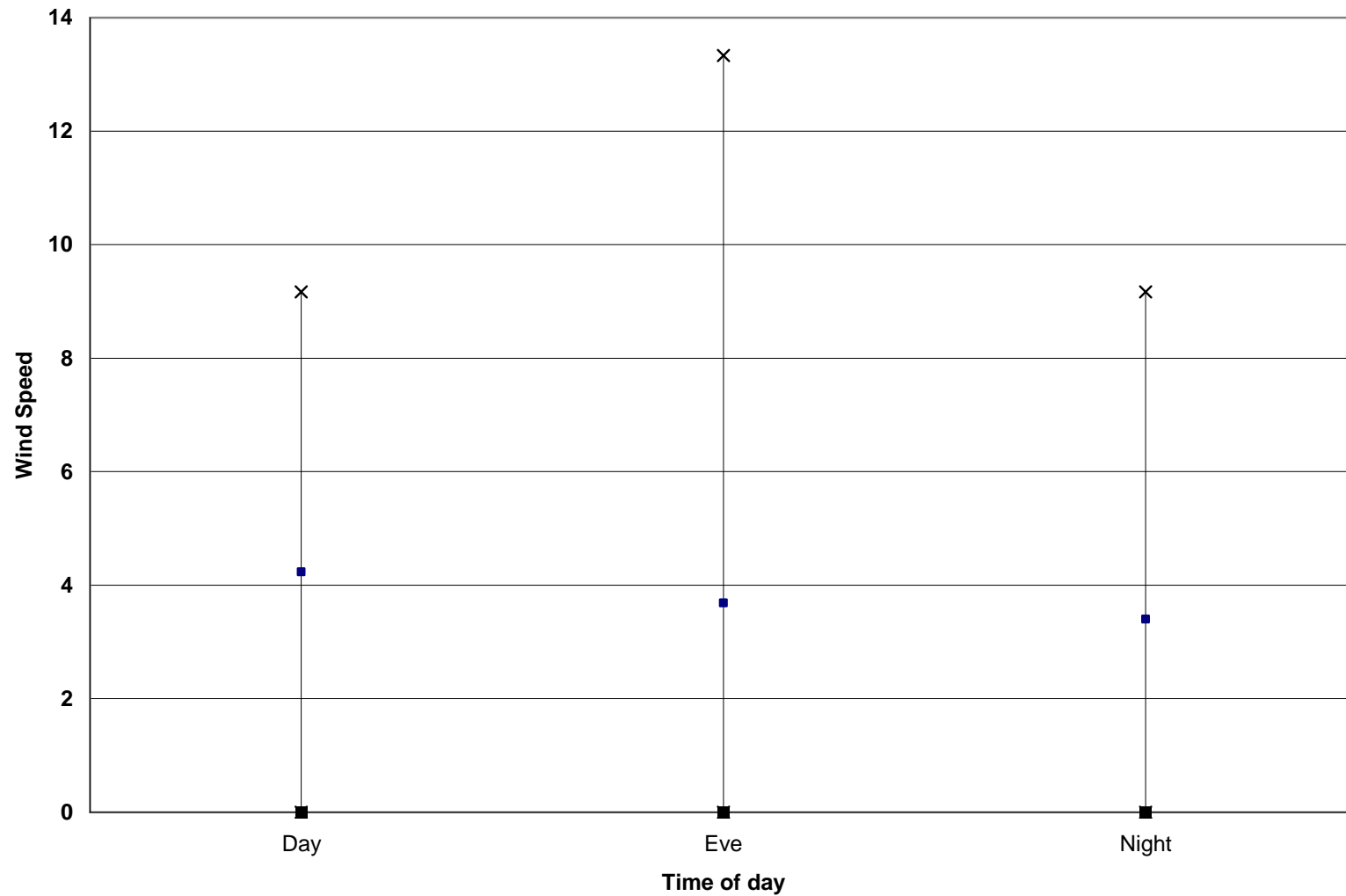
## **APPENDIX D**

### **WEATHER DATA (GODERICH STATION) - WIND POWER OUTPUT DATA (KINGSBRIDGE WIND FARMS) FOR JUNE, JULY & AUGUST 2006**

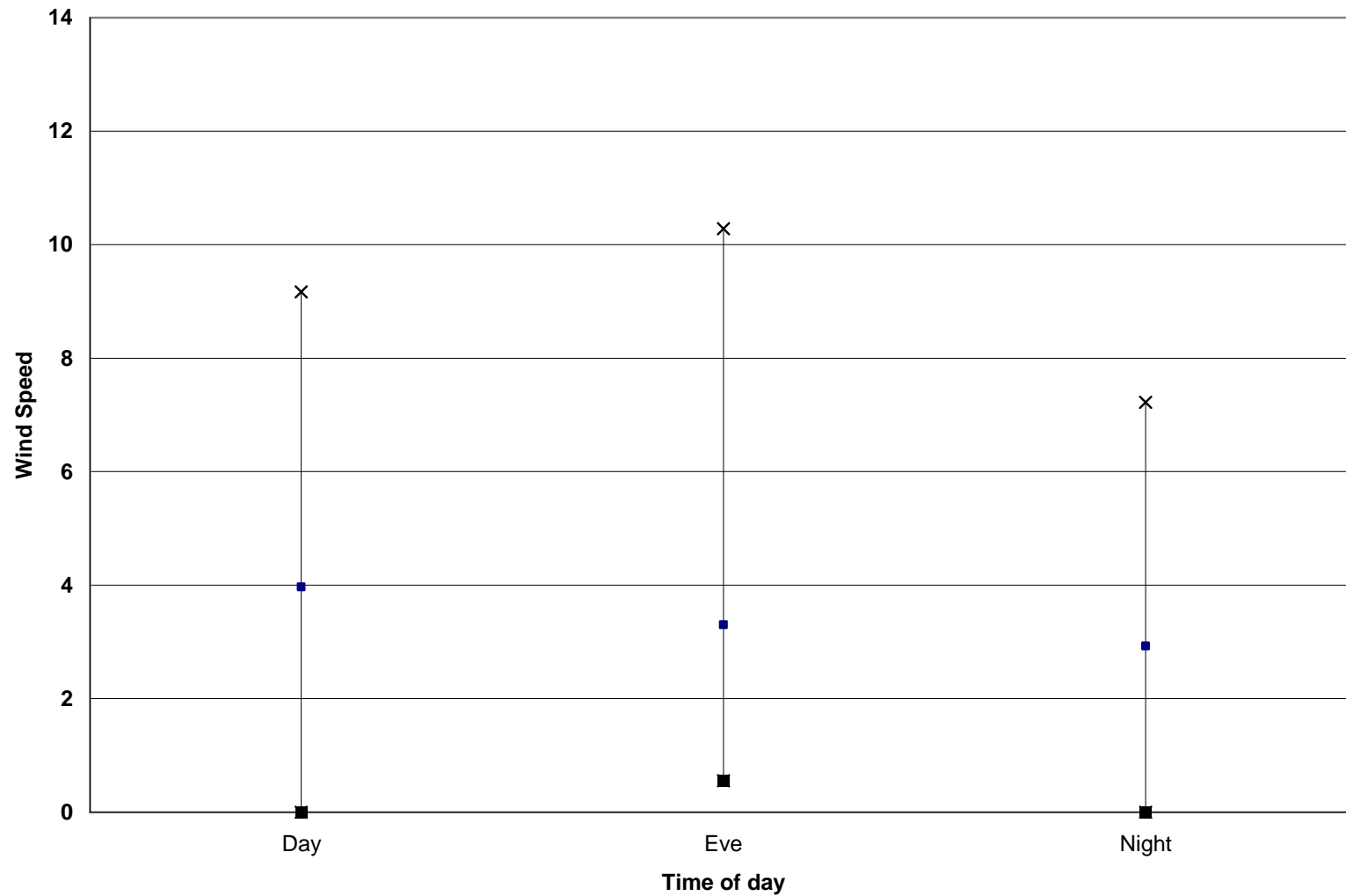
June (Wind Speed vs. time of day)



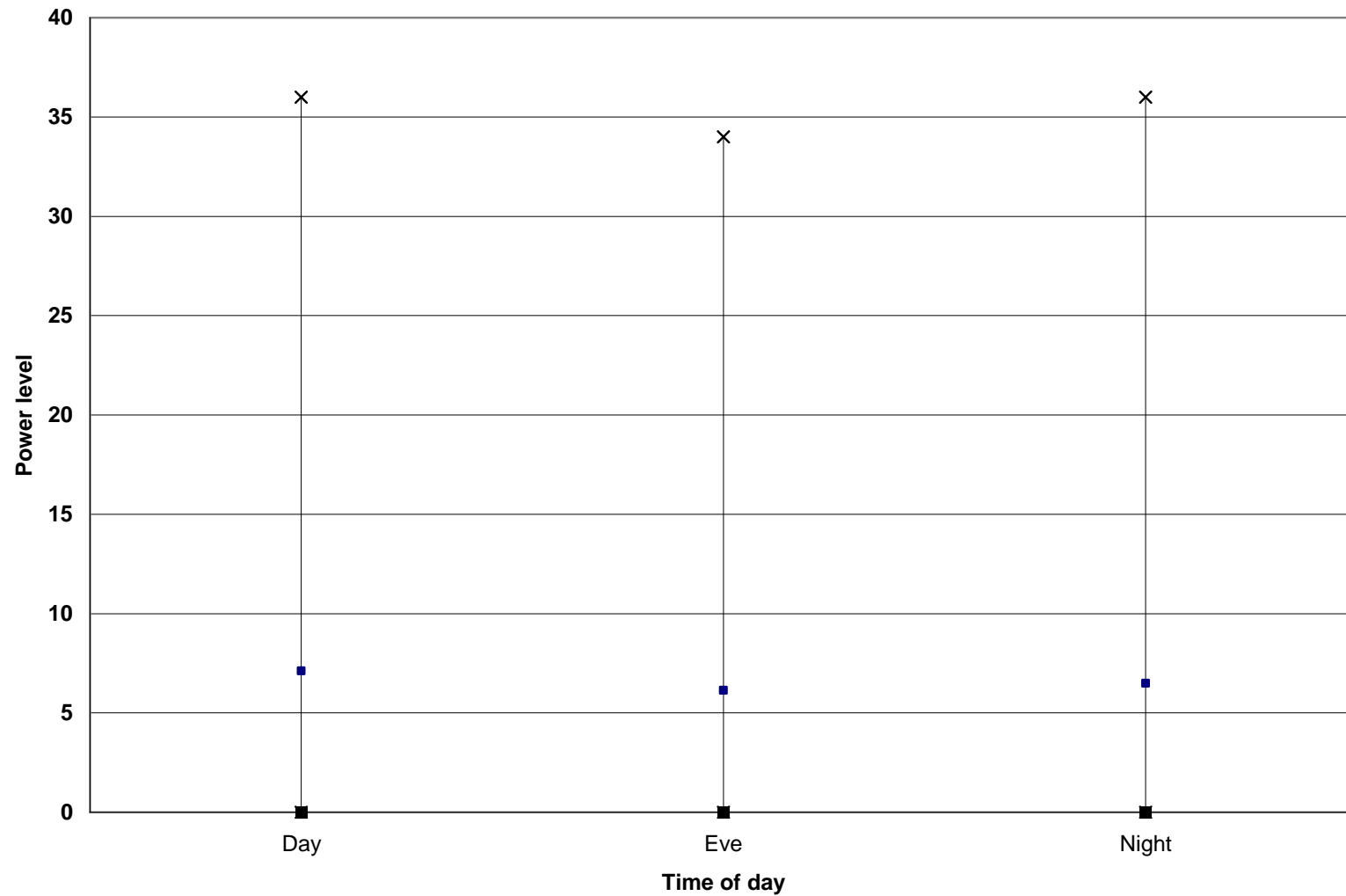
July (Wind Speed vs. time of day)



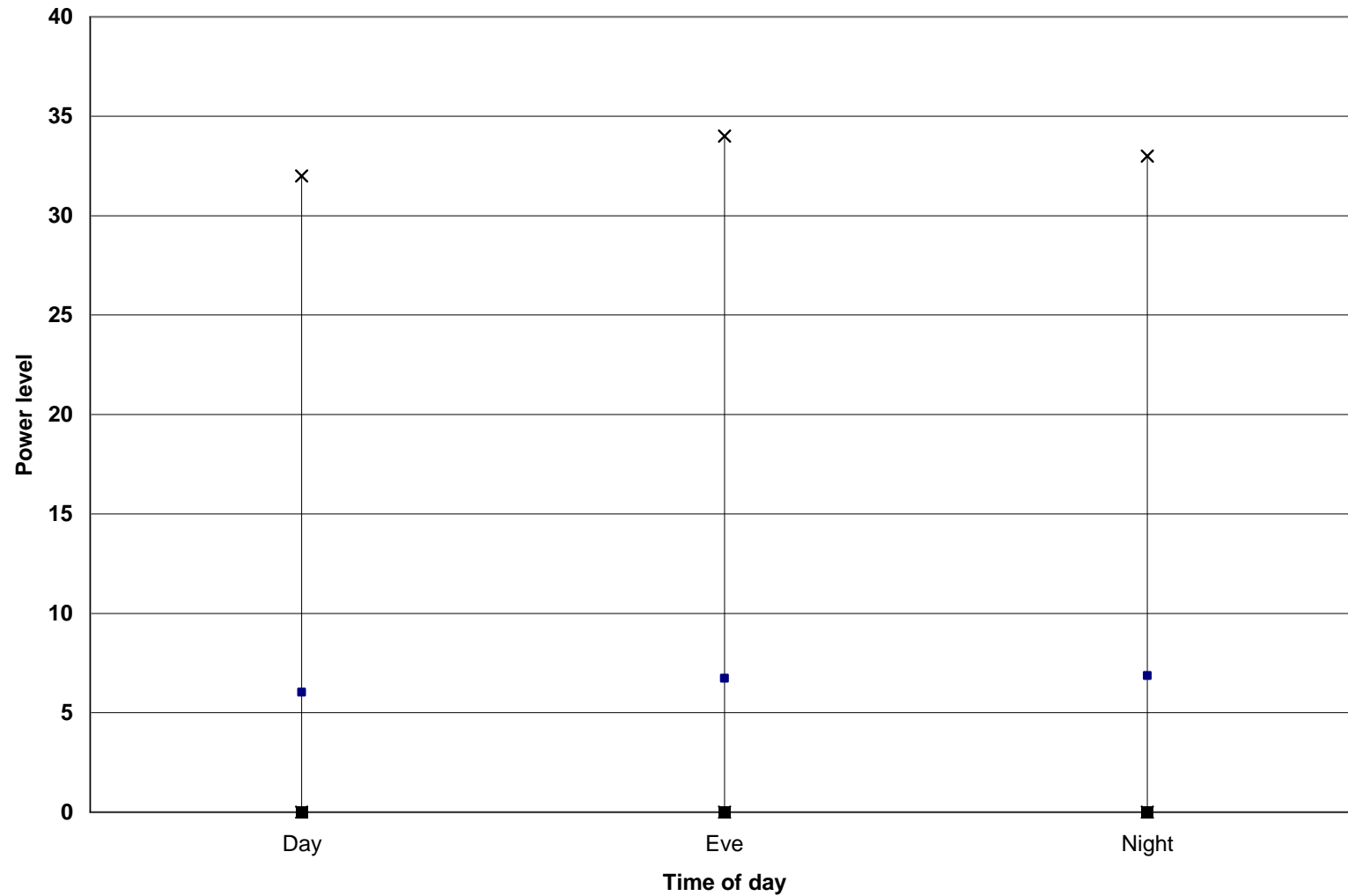
August (wind spd vs. time of day)



June (Pwr vs. time of day)

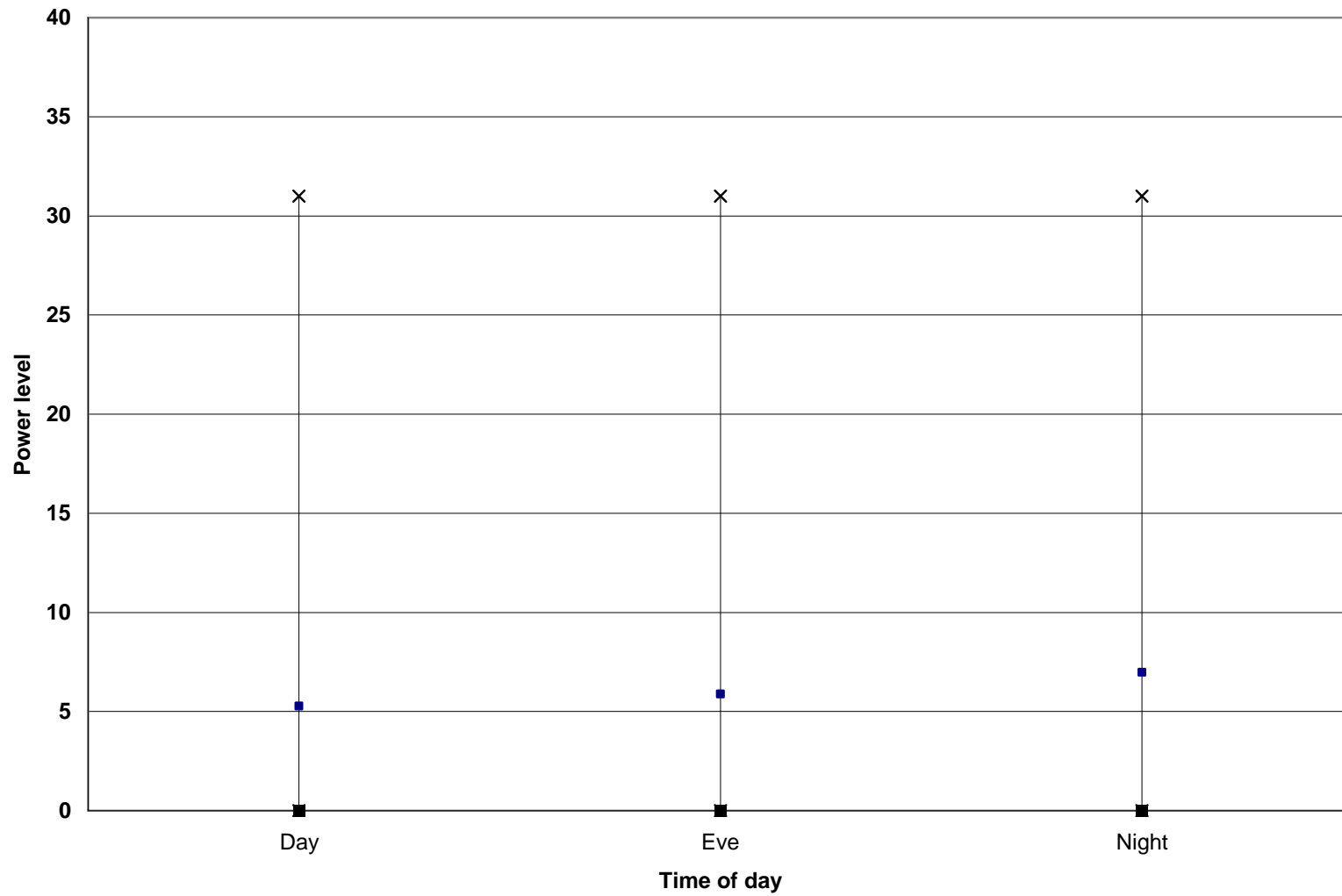


July (Pwr vs. time of day)

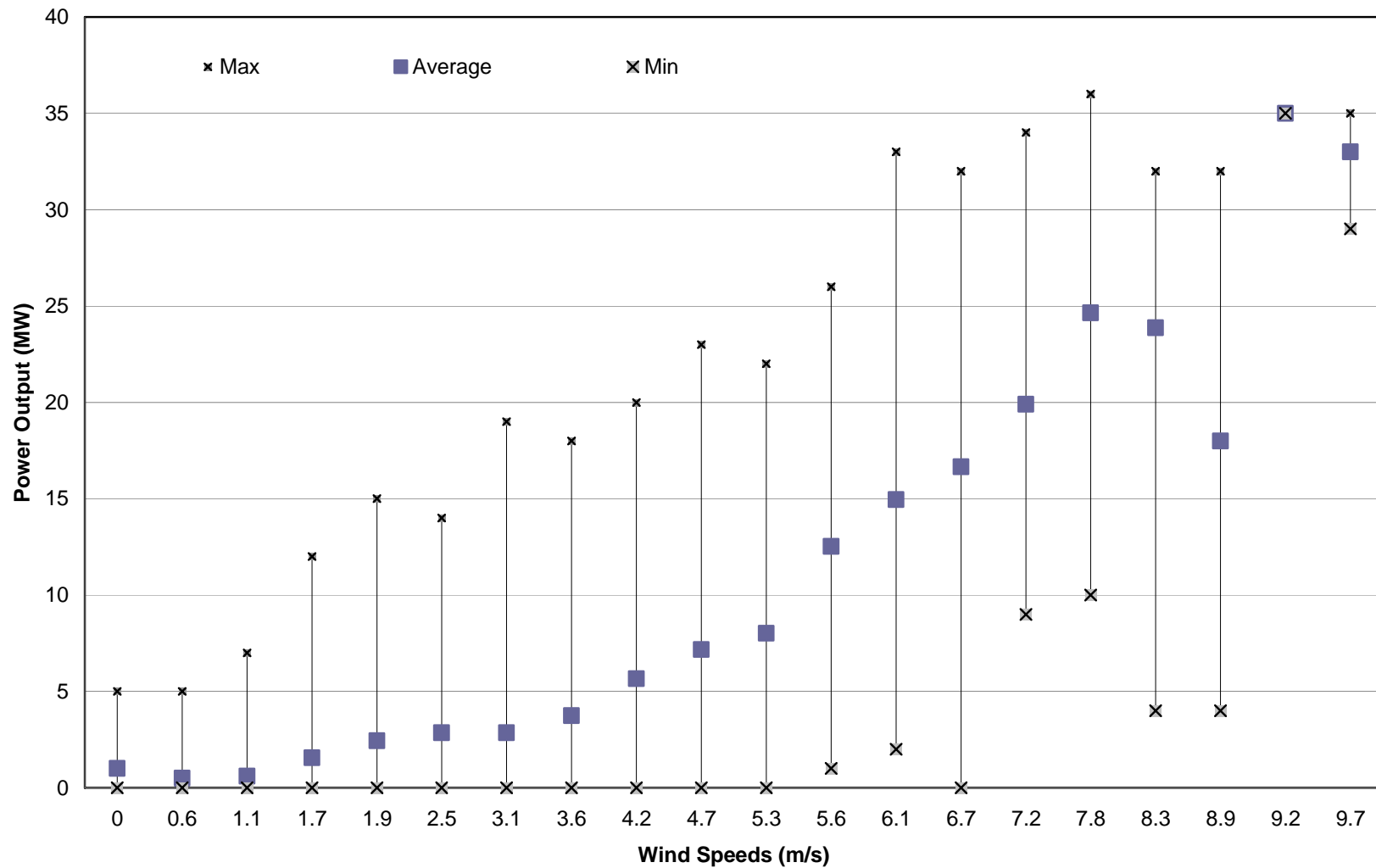




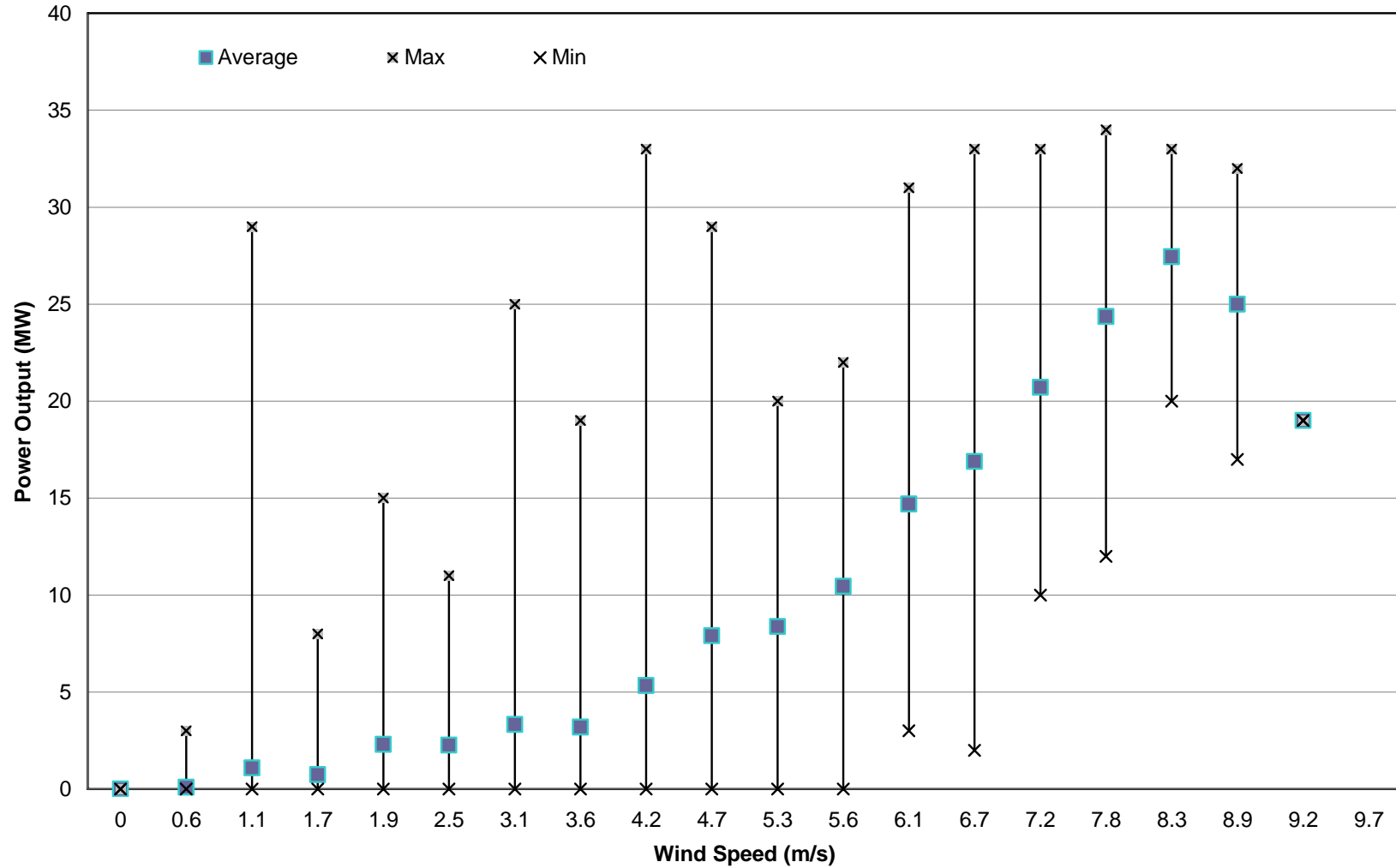
August (Pwr vs. time of day)



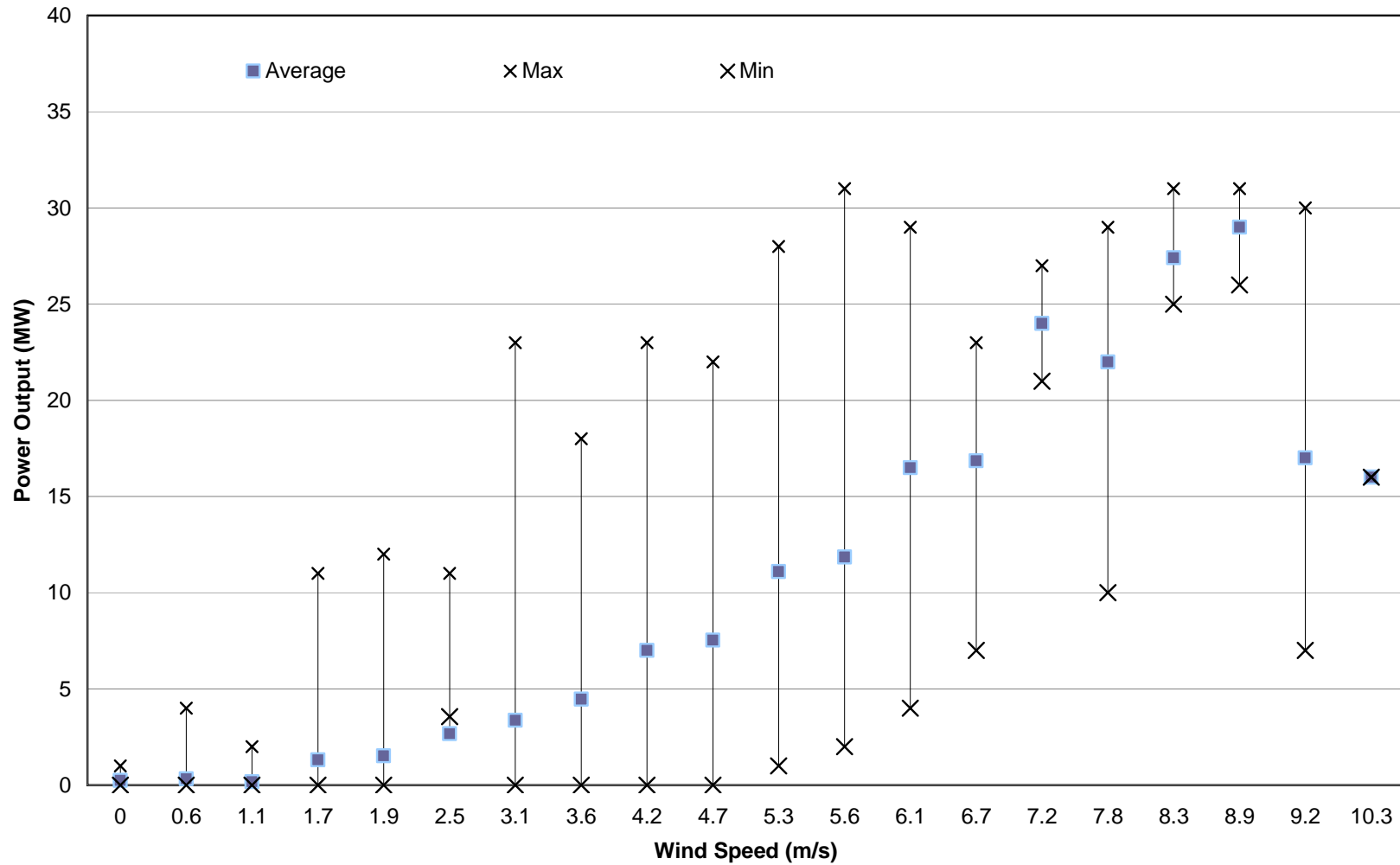
Power Output vs. Wind Speeds for June



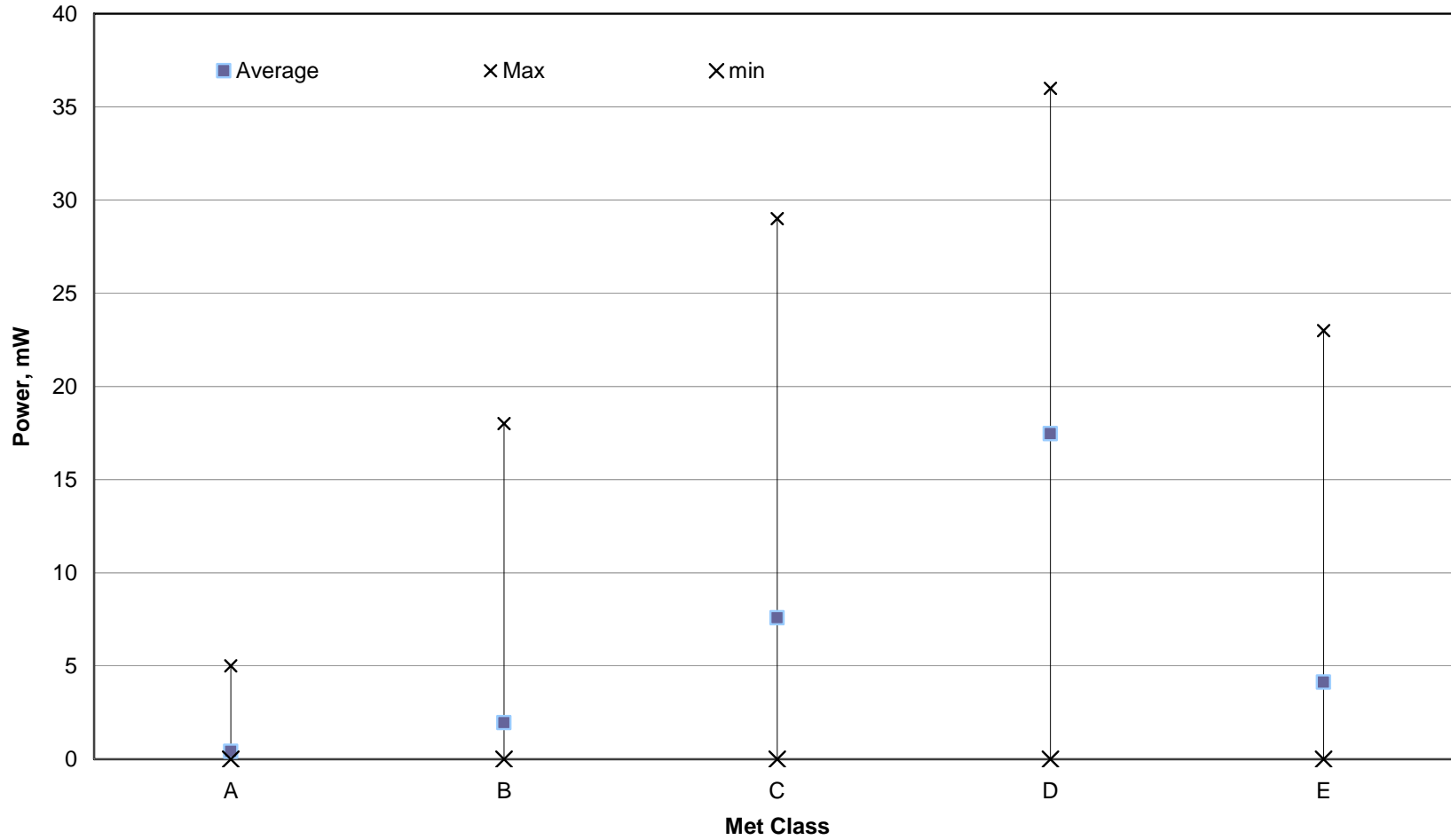
### Max, Average and Min Power output for Month of July



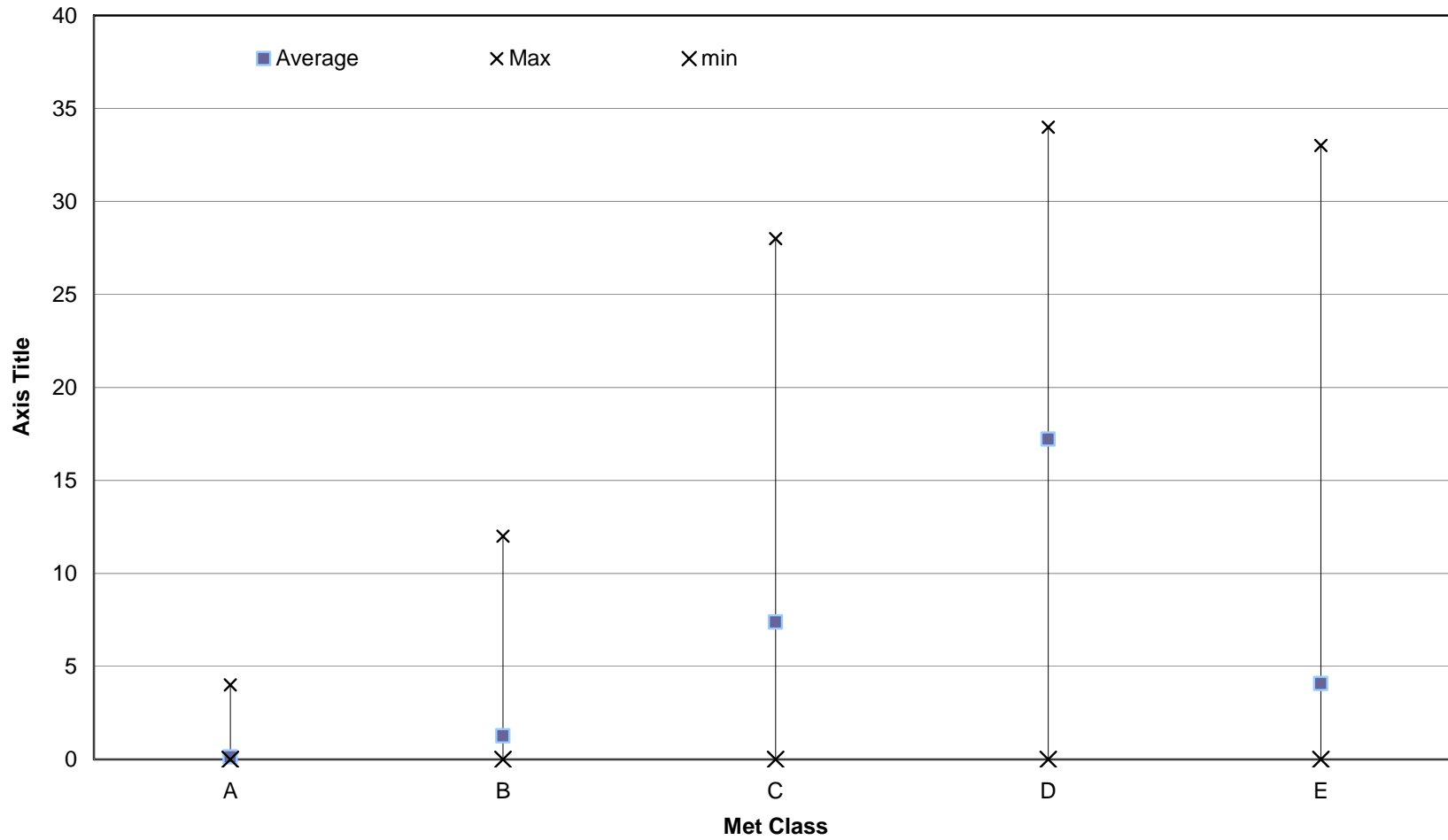
### Max, Average and Min Power output for Month of August



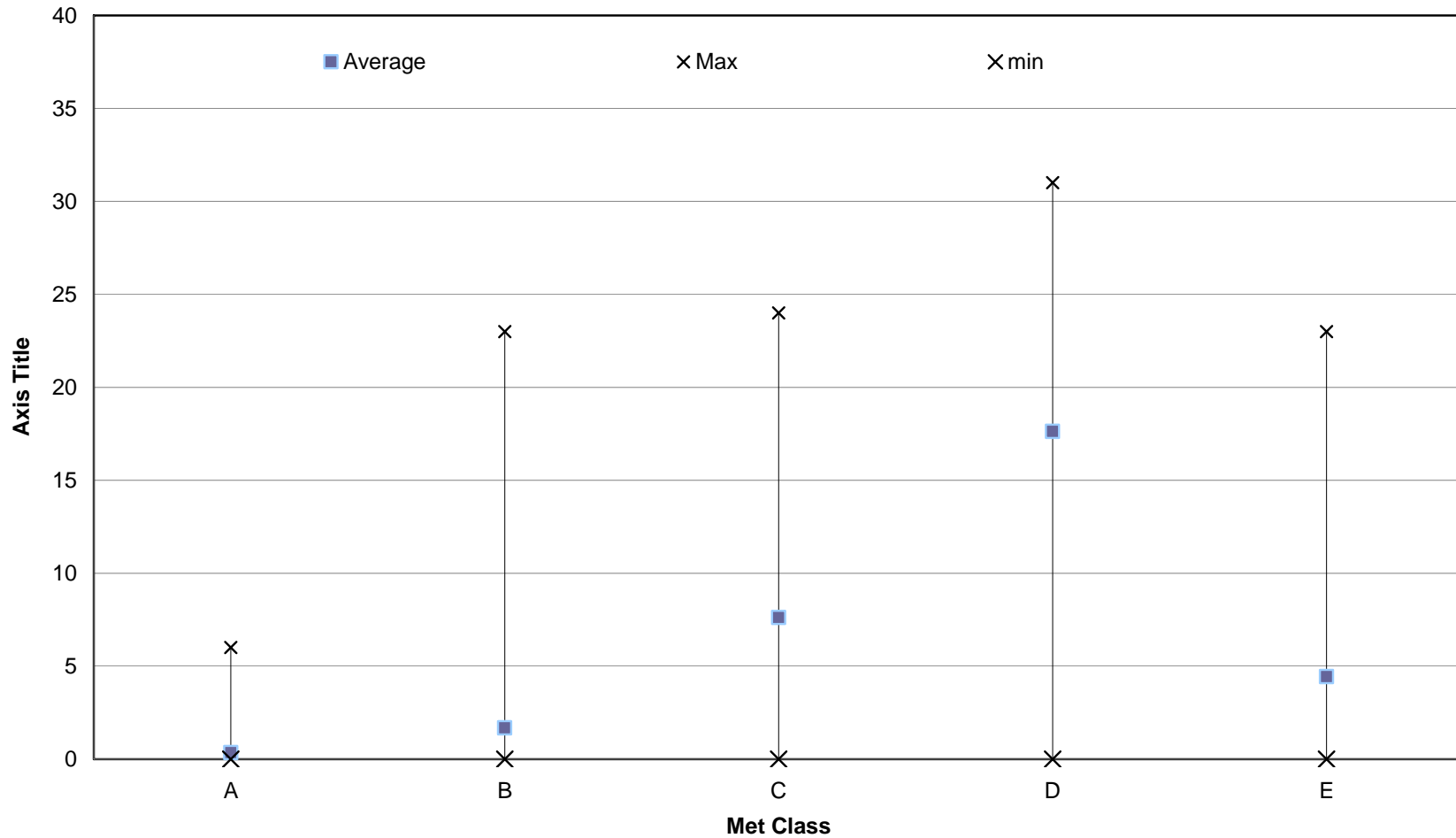
### Max, Average and Min Power output for Month of June vs. Class



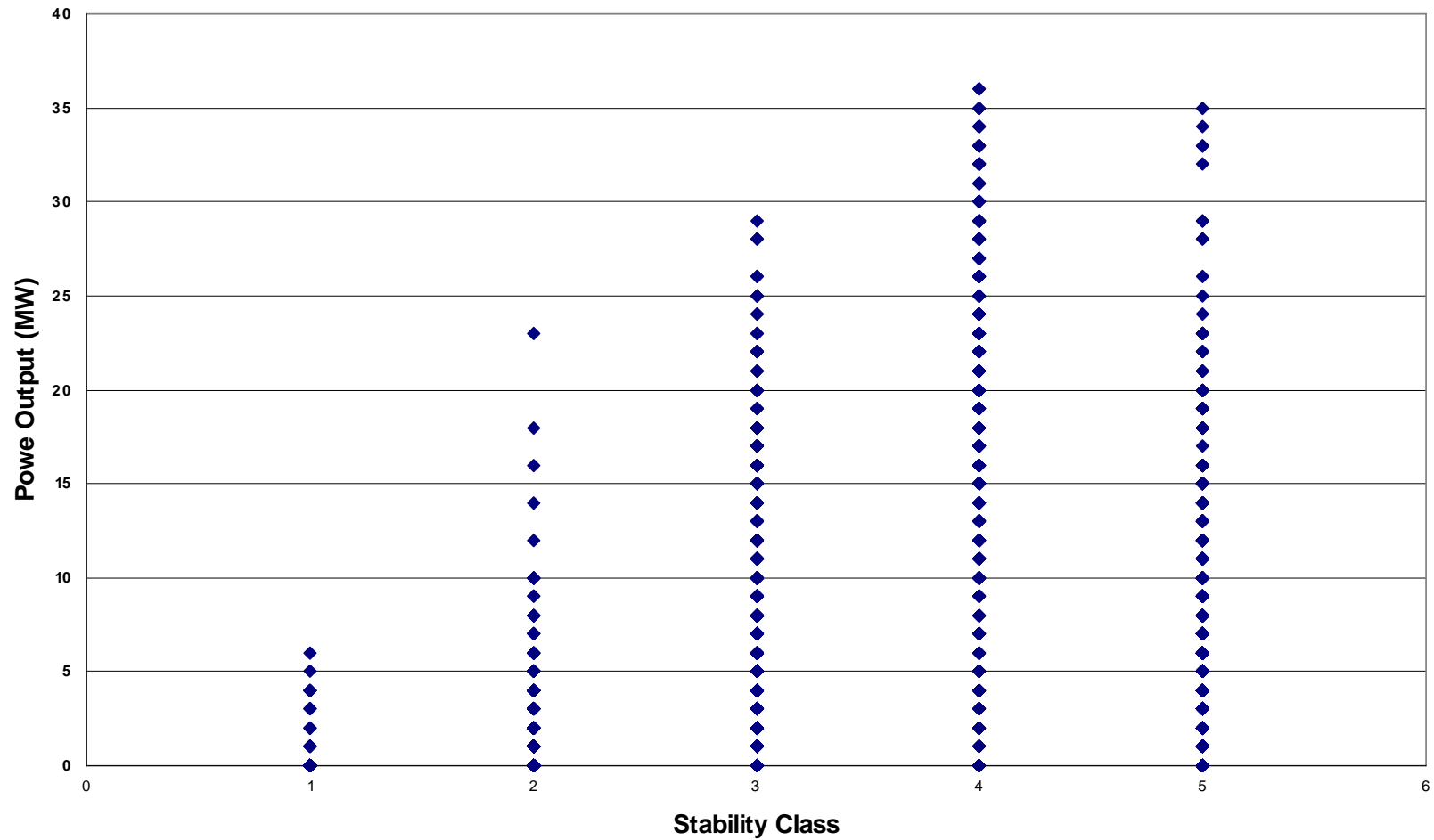
### Max, Average and Min Power output for Month of July vs. Class



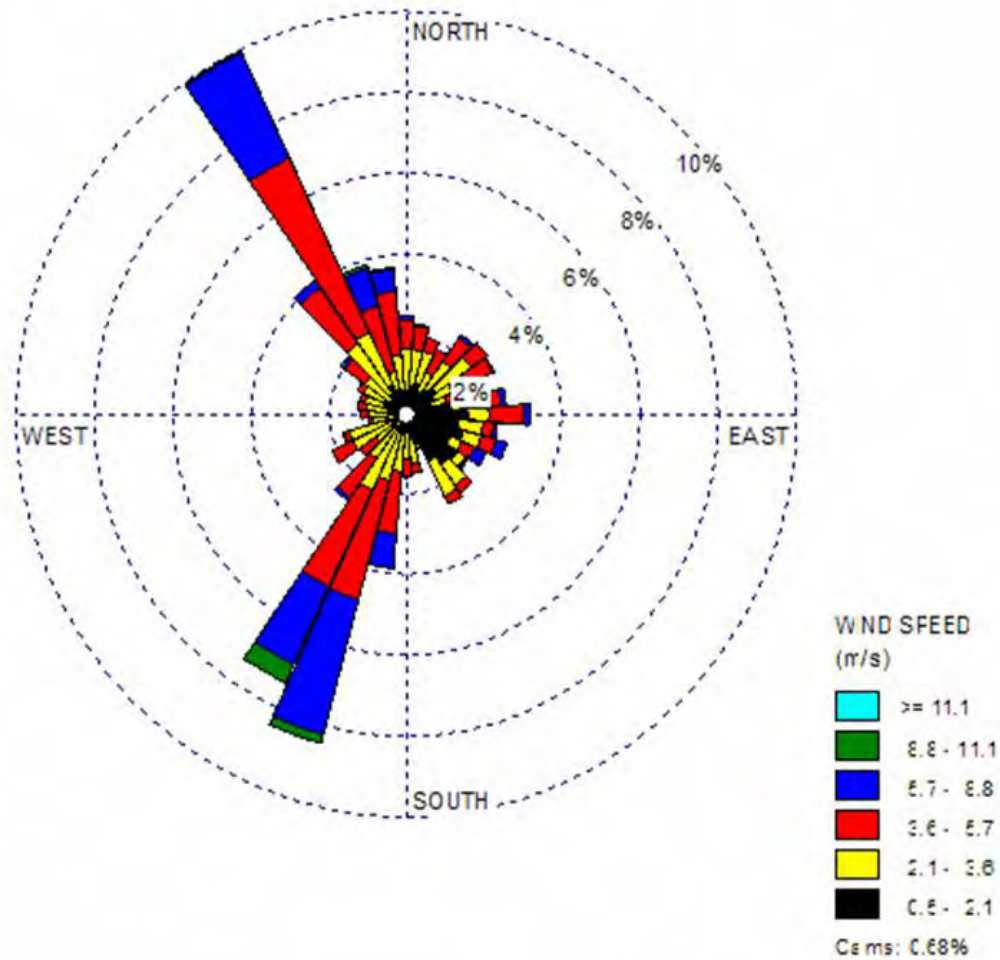
### Max, Average and Min Power output for Month of August vs. Class



**Power Output vs. Stability class for all three months**







**Windrose data for Goderich Station for June, July and August 2006 combined.**

## **APPENDIX E**

### **THE BEATING PHENOMENON**

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## **E1. Background**

One of the main source characteristics that has been attributed to wind turbine noise is they produce swishing sound. Alternate terminologies used for the swishing sound are; beating, thumping, hammer etc. etc. by people being exposed to the wind turbine noise.

G. P. van den berg in his doctoral dissertation, Chapter V-Page 61 (Reference 1) states, “Atmospheric stability is not only relevant for wind turbine sound *levels*, as we saw in he preceding chapter, but also for the *character* of the sound. In conditions where the atmosphere is stable, distant wind turbines can produce a beating or thumping sound that is not apparent in daytime.”

A brief introduction is given in this appendix on the beating phenomenon in acoustics. Some salient points such as ‘tuning process in music’ as well as ‘the subjective reaction’ to beating are also highlighted. Clarification for beating in wind turbine noise is also given in this appendix and attempts will also be made to distinguish the ‘swishing’ phenomenon from ‘the beating’ phenomenon.

Two references are used extensively while preparing this appendix and are:

- E1) *Fundamentals of Acoustics* by L. E. Kinsler and A. R. Frey, Second Edition, John Wiley & Sons, Inc. 1962. ISBN 0 471 46049 5; and
- E2) *Musical Acoustics – An Introduction* by D. E. Hall, Wadsworth Publishing Co. 1980. ISBN 0-534-00758-9.

## **E2. Beats**

A simple scientific definition of ‘Beating’ is: “the linear combination of two simple harmonic vibrations of nearly the same frequency results in the *phenomenon of beats*.”

Without any loss of generality, each of the vibrating wave can be represented by,

$$\text{Wave}_1 = A_1 \sin (f_1 t) \quad \text{and} \quad \text{Wave}_2 = A_2 \sin (f_2 t) \quad (\text{E1})$$

Where,  $A_1$  and  $A_2$  are amplitudes of the two waves and  $f_1$  and  $f_2$  are the frequencies of the two the two waves. When the two waves are summed together, (i.e.) played together, the resulting vibration can be regarded as approximately simple harmonic, with a frequency that lies somewhere between  $f_1$  and  $f_2$  and the amplitude varying slowly at a frequency of  $(f_1 - f_2)$  and we have assumed that  $f_1$  is larger than  $f_2$ . The amplitude of the combined wave will 'wax' and 'wane' between the two limits  $(A_1 + A_2)$  and  $(A_1 - A_2)$ .

In the case of sound waves, the simultaneous sounding of two pure tones of slightly different frequency, the above variation in amplitude results in a rhythmic pulsing of the loudness of the sound which occurs at a rate corresponding to the difference in frequency,  $(f_1 - f_2)$ , of the two sounds and is known as *beating*. Audible beats are heard whenever two sound of nearly the same frequency strike the ear, and when the frequency of each component is within the audible range. If the frequency difference is small, about 10 or less cycles per sec, the resulting sound waxes and wanes at this rate, with an apparent pitch corresponding to the average frequency. If, on the other hand, their frequency difference is about 200 cycles per sec or more, a combination tone may be observed whose frequency is equal to the difference between that of the two sounds. For intermediate frequency differences, the sound has a rough and discordant character.

A graphical representation of the onset and disappearance of the *beating* phenomenon is highlighted through a series of plots generated from two sounds and are shown in Figures E1 through E7 below.

Figure E1. The Beat Phenomenon

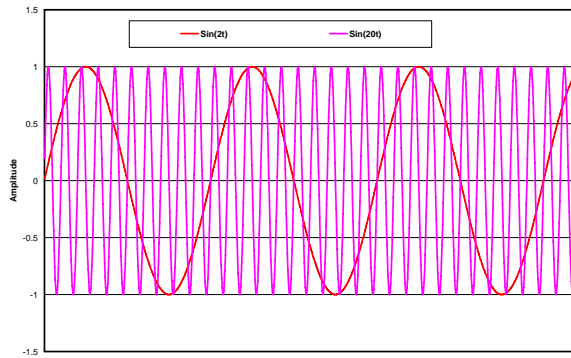


Figure E4. The Beat Phenomenon

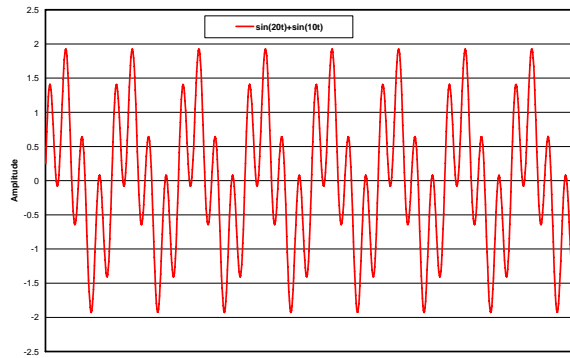


Figure E2. The Beat Phenomenon

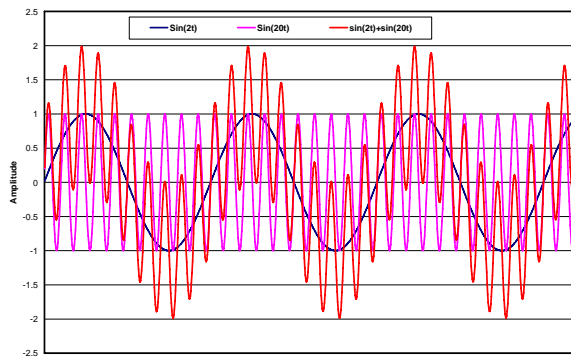


Figure E5. The Beat Phenomenon

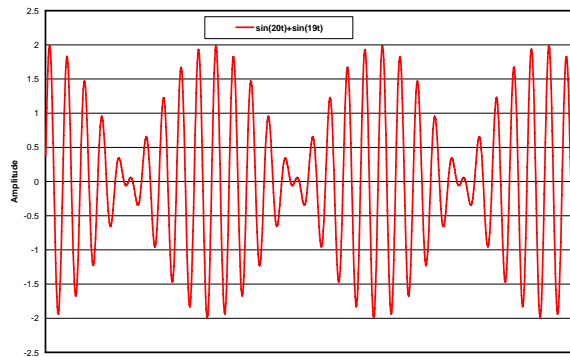


Figure E3. The Beat Phenomenon

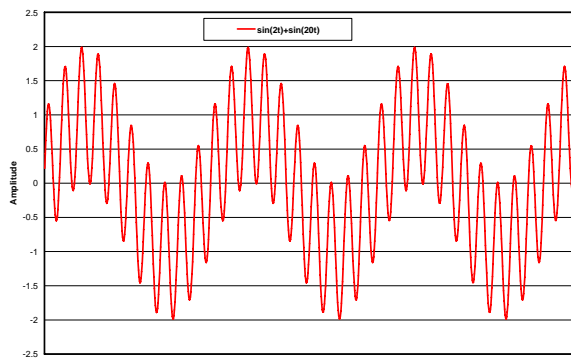
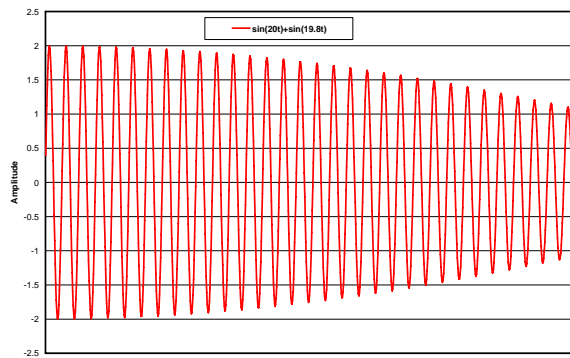


Figure E6. The Beat Phenomenon



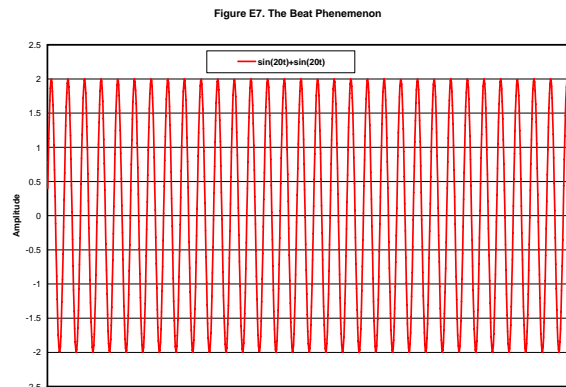


Figure E1 shows two simple sound waves at frequencies of 2 and 20 cycles per second, with their sum shown in Figure E2. One can see frequencies 2 and 20 as well as the beat frequency of 18. The *beat* is not as pronounced since the beat rate is close to the frequency of one of the two sounds as seen in Figure E3. The difference in the two frequencies is 10 in the ‘beating’ shown in Figure E4. The true ‘beating’ is not clear in Figure E4 since the beating rate is 10. Figures E5 and E6 show true *beat*. The amplitude is changing between 0 and 1 at a beat rate of 1 and 0.2.

### E3. Subjective Response

If the sounds are within audible range, the resulting sound is heard as a single sound whose loudness varies smoothly and rhythmically at the beat rate, and it is said that the sounds *beat* with each other. Actually, the beating phenomenon is used by musical instrument tuners to tune, precisely by observing the beating and adjust for “zero” beat.

The main subjective effect of the ‘beating phenomenon’ is that the resulting sound appears harsh and discordant. The level of such a response is based on the beat rate as well as the level of the sound. At low levels of the sound, say less than 50 to 60 dB, the only effect is that waxing and waning of the sound.

## **APPENDIX F**

### **AN ASSESSMENT PROCEDURE**

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## **F1. Background**

One of the main concerns with the assessment procedures used by different jurisdictions, except New Zealand, is that the effects of meteorological conditions were not appropriately accounted for. Even the New Zealand approach accounts for the effect of wind shear by applying the wind speed data at each site, measured at the hub-height.

It was stated earlier that the current procedures in Ontario are very simple to apply and were similar to other jurisdiction in Europe. The procedure does not require the establishment of ambient sound levels at affected receptor locations before the installation of the wind farm. Neither is there a requirement to incorporate the prevailing meteorological conditions at the proposed wind farm site. Below is an example of one possible assessment process that could address the above concerns. Additional research and analysis would be required in order to develop an appropriate assessment process.

- i. Following the standard procedures used in New Zealand, the ambient sound levels are to be monitored for a pre-set time, say for a month, at salient points of reception. The data should be collected in intervals of 10 minutes so as to be able to evaluate statistically valid analysis;
- ii. The prevailing weather conditions, wind speed, direction, stability class are also measured at the wind farm site for the same duration and time intervals;
- iii. The meteorological data is collected at a minimum of two heights (say 10 m and at hub-height);
- iv. The analysis would involve correlation between wind profiles, determination of shear coefficients (similar to the schemes reported in Reference 22), support for the argument of hub-height wind speeds;
- v. The noise prediction models, for the proposed wind farm, will include the effect of dominant scenarios of meteorological conditions and evaluate the potential range of noise levels;



- 
- vi. One would then assign suitable assessment conditions, based on appropriate statistical parameters, for the range of noise levels that can be expected at the salient points of receptions. Some preliminary concepts of this are:
    - a) Establish the noise levels at all salient receptor locations by applying the current MOE procedures;
    - b) Establish the expected increase in turbine sound power levels, by using the measured Meteorological (MET) data, and re-evaluate the noise levels at all the receptor locations;
    - c) Establish the dominant wind direction from the MET data and its percentage of occurrence. Most of the commercially available propagation models are able to incorporate basic MET data. Using the wind direction data, re-evaluate the noise levels at all salient receptor locations;
    - d) The results of Steps (a) thru' (c) would aid in setting up statistical analysis of noise levels, its variability and the number of affected residents. Average conclusions about the noise impact and potential mitigation methods if necessary can be established.
  
  - vii. Compliance of the wind farm site and potential adverse noise effects, based on acceptable annoyance criterion, can thus be included in the impact analysis to determine the suitability of the wind farm proposal.

The above process is one possible suggestion of the ways in which the current procedures can be revised to incorporate local meteorological conditions at the proposed wind farm sites.

# INFRASOUND FROM WIND TURBINES – FACT, FICTION OR DECEPTION

Geoff Leventhall

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## ABSTRACT

Infrasound is discussed in terms of what it actually is, how the media has dealt with it and what those with limited knowledge say about it. The perception of infrasound occurs at levels higher than the levels produced by wind turbines and there is now agreement amongst acousticians that infrasound from wind turbines is not a problem. Statements on infrasound from objectors are considered and it is shown how these may have caused avoidable distress to residents near wind turbines and also diverted attention from the main noise source, which is the repeating sound of the blades interacting with the tower. This is the noise which requires attention, both to reduce it and to develop optimum assessment methods

## RÉSUMÉ

L'infrason est discuté en termes de ce qu'il est réellement, son traitement dans les médias et par ceux avec des connaissances limitée à son sujet. La perception de l'infrason est qu'il existe à des niveaux plus hauts que ceux produits par des éoliennes, mais il y a maintenant accord parmi les acousticiens que l'infrason des éoliennes n'est pas un problème. Des rapports sur l'infrason par des protestataires sont considérés et on montre comment ceux-ci ont pu causer de la détresse évitable aux résidents près des éoliennes et également diverter l'attention de la source principale de bruit: le son répétitif de l'interaction des lames avec la tour. C'est ce bruit qui exige de l'attention, pour le réduire et pour développer des méthodes optimales d'évaluation.

## 1. INFRASOUND

A definition of infrasound is: Acoustic oscillations whose frequency is below the low frequency limit of audible sound (about 16Hz). (IEC 1994)

This definition is incorrect, as sound remains audible at frequencies well below 16Hz. For example, measurements of hearing threshold have been made down to 4Hz for exposure in an acoustic chamber (Watanabe and Møller 1990b) and down to 1.5 Hz for earphone listening (Yeowart, Bryan et al. 1967)

The limit of 16Hz, or more commonly considered as 20Hz, arises from the lower frequency limit of the standardized equal loudness hearing contours measured in units of phons, which is a difficult measurement at low frequencies, not from the lower limit of hearing.

## 2. THE AUDIBILITY OF INFRASOUND

Hearing sensation does not suddenly cease at 20Hz when the frequency is reduced from 21Hz to 19Hz, but continues from 20Hz down to very low frequencies of several Hertz. It is not possible to define an inaudible infrasound range and an audible audio range as separate regions, unless the infrasound range is limited to naturally occurring infrasound of very low frequencies. The range from about 10Hz to 100Hz can be

considered as the low frequency region, with possible extensions by an octave at each end of this range, giving 5Hz to 200Hz. There is a very fuzzy boundary between infrasound and low frequency noise, which often causes confusion.

Hearing thresholds in the infrasonic and low frequency region are shown in Fig 1. The solid line above 20Hz is the low frequency end of the ISO standard threshold (ISO:226 2003). The dashed curve, 4Hz to 125Hz, is from Watanabe and Møller (Watanabe and Møller 1990b). There is good correspondence between the two threshold measurements in the overlap region.

The slope of the hearing threshold reduces below about 15Hz from approximately 20dB/octave above 15 Hz to about 12dB/octave below. (Yeowart, Bryan et al. 1967). The common assumption that "infrasound" is inaudible is incorrect, arising from an unfortunate choice of descriptor. "Real" infrasound, at levels and frequencies below audibility are largely natural phenomena, although human activities, such as explosions, also produce infrasound. Microphone arrays for the detection of airborne infrasound are a component of the monitoring for the Nuclear Test Ban Treaty

The median hearing threshold is not a simple delineation between "Can hear - Can't hear", but the threshold is rather variable between individuals, depending on their genetics, prior noise exposure and age (ISO7029 2000). The standard deviation of threshold measurements is typically about 6dB.

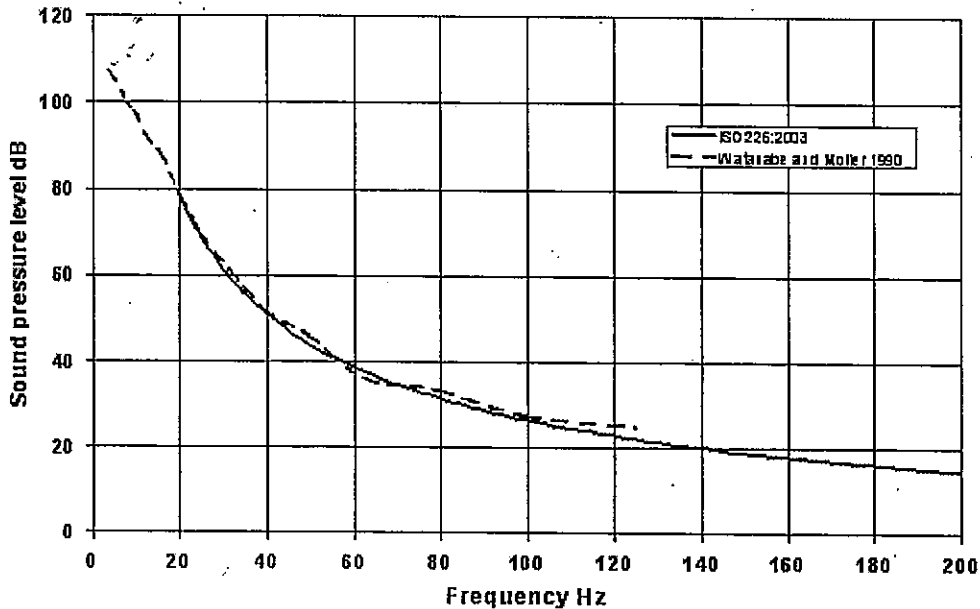


Figure 1. Infrasonic and low frequency threshold

Therefore, it is most unlikely that anyone will be able to hear sound at any frequency which is more than, say, 20dB below its median threshold.

The false concept that infrasound is inaudible, when coupled with the many common misconceptions about its subjective effects, has spawned concerns, particularly expressed in popular publications, which are best described as mythology, rather than fact.

A report reviewing low frequency noise (Leventhall, Benton et al. 2003) is available on the internet.

**High levels at very low frequencies:** These may result in aural pain, which is not a hearing sensation, but arises from displacements of the middle ear system beyond its comfortable limits. Persons with both hearing ability and hearing loss, and with normal middle ears, exhibit aural pain at a similar stimulus level, which is at about 165dB at 2Hz, reducing to 145dB at 20Hz. Static pressure produces pain at 175 -180dB, whilst eardrum rupture occurs at 185 -190dB (von Gierke and Nixon 1976). A pressure of  $5 \times 10^4$  Pa, which is about half atmospheric pressure, falls in the 185 -190dB range. A child on a swing experiences infrasound at a level of around 110dB and frequency 0.5Hz, depending on the suspended length and the change in height during the swing.

**Natural infrasound:** We are enveloped in naturally occurring infrasound, which is in the range from about 0.01 Hz to 2Hz and is at inaudible levels. The lower limit of one cycle in a hundred seconds separates infrasound, as a propagating wave, from all but the fastest fluctuations in barometric pressure. There are many natural sources of infrasound, including meteors, volcanic eruptions, ocean waves, wind and any effect which leads to slow oscillations of the air. Man made sources include explosions, large combustion processes, slow speed fans and machinery. Much natural infrasound is lower

in frequency than 1 Hz and below the hearing threshold. (Beard and George 2000). Our evolution has been in the presence of natural infrasound.

**Alternative receptors:** The question arises of whether there is a hierarchy of receptors, of which the ear is the most sensitive except at the lower frequencies, when other receptors may come into prominence. Several vibration and contact detectors reside in the skin, covering different frequency ranges (Johnson 2001). The Pacinian corpuscles are the most sensitive, with a threshold displacement of about 0.002mm in the region of 200Hz. Their sensitivity into lower frequencies reduces at approximately 50dB per decade from the maximum sensitivity.

The threshold displacement of 0.002mm at 200Hz is similar to the particle displacement in air of a 200Hz sound wave of 94dB (1 Pa) pressure. Since the particle displacement in a sound wave of fixed pressure doubles as the frequency is halved (20dB per decade) inaudible sound waves will not excite these subcutaneous receptors.

There is no reliable evidence that infrasound at levels below its hearing threshold has an adverse effect on the body (Berglund and Lindvall 1995). A recent French study of wind turbine noise confirms that infrasound from wind turbines is not a problem. (Chouard 2006)

**Body vibrations:** It is known that high levels of low frequency noise excite body vibrations (Leventhall, Benton et al. 2003). The most prominent body response is a chest resonance vibration in the region of 50Hz to 80Hz, occurring at levels above about 80dB, which are audible in this frequency range. The low frequency perception thresholds of normal hearing and profoundly deaf subjects have also been investigated (Yamada, Ikuji et al. 1983), when it was shown that the profoundly deaf subjects perceived noise through their body

only at levels which were in excess of normal thresholds. The threshold of sensation of the deaf subjects was 40-50dB above the hearing threshold of those with normal hearing up to a frequency of 63Hz and greater at higher frequencies. For example about 100dB greater at 1 kHz, at which level perception was by the subjects' residual hearing. Deaf subjects experienced chest vibration in the same frequency range as normal hearing subjects.

The much repeated statement that "infrasound can be felt but not heard" is not supported by these measurements. The erroneous thought processes which led to this confusion are possibly:

Infrasound causes body vibrations - (correct at very high levels)

But infrasound is inaudible - (not correct at very high levels)

Therefore infrasound can be felt but not heard - (not correct)

neglecting that the levels to produce body vibrations are well above the hearing threshold. But, as will be shown later, infrasound is not a problem for modern wind turbines.

**The dimensions of noise:** Noise is multidimensional. A one dimensional view of noise is the A-weighting, which considers only levels and neglects frequencies. Another one-dimensional view is to consider only frequencies and neglect levels. Developing the dimensions further, two dimensions include both frequency and level (the spectrum), three dimensions adds in the time variations of the noise, whilst higher dimensions include subjective response.

Many lay people take the one dimensional view of infrasound, which is based on frequency alone. They express concern at the presence of any infrasound, irrespective of its level. This is a significant failure of understanding.

**Public Perceptions:** The Public has been misled by the media about infrasound, resulting in needless fears and anxieties, which possibly arise from confusion of the work on subjective effects, which has been carried out at high, audible levels with the popular mindset that infrasound is inaudible. There have also been misunderstandings fostered in publications and popular science books, considered later.

Early work on low frequency noise and its subjective effects was stimulated by the American space program. Launch vehicles produce high noise levels with maximum energy in the low frequency region. Furthermore, as the vehicle accelerates, the crew compartment is subjected to boundary layer turbulence noise for about two minutes after lift-off. Experiments were carried out in low frequency noise chambers on short term subjective tolerance to bands of noise at very high levels of 140 to 150dB, in the frequency range up to 100Hz (Mohr, Cole et al. 1965). It was concluded that the subjects, who were experienced in noise exposure and who were wearing ear protection, could tolerate both broadband and discrete frequency noise in the range

1 Hz to 100Hz at sound pressure levels up to 150dB. Later work suggests that, for 24 hour exposure, levels of 120-130dB are tolerable below 20Hz. These limits were set to prevent direct physiological damage, not for comfort. (Mohr, Cole et al. 1965; Westin 1975; von Gierke and Nixon 1976).

The American work did not attract media attention, but in the late 1960's two papers from France led to much publicity and speculative exaggerations. (Gavreau, Condat et al. 1966; Gavreau 1968). Although both papers carry "infrasound" in their titles, there is very little on frequencies below 20Hz (Leventhall 2005). Some rather casual and irresponsible experiments of the "try it and see" variety were carried out on exposure of the laboratory staff, primarily using high intensity pneumatic sources at frequencies mainly at the upper end of the low frequency range, or above. For example, 196Hz at 160dB sound level and 340Hz at 155dB sound level. A high intensity whistle at 2600Hz is also included in the "infrasound" papers:

*Infrasounds are not difficult to study but they are potentially harmful. For example one of my colleagues, R Levavasseur, who designed a powerful emitter known as the 'Levavasseur whistle' is now a victim of his own inventiveness. One of his larger whistles emitting at 2600Hz had an acoustic power of 1 kW. ... This proved sufficient to make him a lifelong invalid. (Gavreau 1968)*

Of course, 2600Hz is not infrasound, but the misleading implication is that infrasound caused injury to Levavasseur. A point source of sound of power 1 kW will produce a sound level of about 140dB at 1 m, which is a very undesirable exposure at 2600Hz.

Referring to the exposure of 160dB at 196Hz:

*...after the test we became aware of a painful 'resonance' within our bodies - everything inside us seemed to vibrate when we spoke or moved. What had happened was that this sound at 160 decibels..... acting directly on the body produced intense friction between internal organs, resulting in severe irritation of the nerve endings. Presumably if the test had lasted longer than five minutes, internal haemorrhage would have occurred. (Gavreau 1968)*

96 Hz is not infrasound, but the unpleasant effects at 160dB are described in a paper which is said to be about "Infrasound". Internal haemorrhage is often quoted as an effect of exposure to infrasound. Exposure levels were not given for frequencies of 37Hz and 7Hz, although the 7Hz caused subjective disturbance and vibrations of the laboratory walls. Unfortunately, these papers by Gavreau were seized upon by the press and presented to claim that infrasound was dangerous. For example "The silent killer all around us", London Evening News, 25 May 1974. When work by other investigators detected moderate levels of infrasound in, for example, road vehicles, the press was delighted, leading to "The silent sound menaces drivers" - Daily Mirror, 19 October 1969.

"Danger in unheard car sounds" The Observer, 21 April 1974.

The most deplorable example, in a book which claimed to have checked its sources, was in "Supernature" by Lyall Watson (Coronet 1973). In this it is claimed that the technician who gave one of Gavreau's high power infrasound sources its trial run "fell down dead on the spot" and that two infrasonic generators "focused on a point even five miles away produce a resonance that can knock a building down as effectively as a major earthquake".

These fictitious statements are, of course, totally incorrect but are clear contributors to some of the unfounded concerns which the public feels about infrasound. One can detect a transition from Gavreau and his colleague feeling ill after exposure to the high level of 196Hz to "fell down dead on the spot" and a further transition from laboratory walls vibrating to "can knock a building down", transitions which resulted from repeated media exaggerations over a period of five or six years.

The misunderstanding between infrasound and low frequency noise continues to the present day. A newspaper article on low frequency noise from wind turbines (Miller 24 January 2004), opens with:

Onshore wind farms are a health hazard to people living near them because of the low-frequency noise that they emit, according to new medical studies. A French translation of this article for use by objectors' groups opens with:

*De nouvelles etudes medicales indiquent que les eoliennes terrestres representent un risque pour la sante des gens habitant a proximite, a cause d'emission d'infrasons.*

The translation of low frequency noise into infrasons continues through the article. This is not a trivial misrepresentation because, following on from Gavreau, infrasound

has been connected with many misfortunes, being blamed for problems for which some other explanation had not yet been found e.g., brain tumours, cot deaths of babies, road accidents.

Infrasound, and its companion low frequency noise, now occupy a special position in the national psyche of a number of countries, where they lie in wait for an activating trigger to re-generate concerns of effects on health. Earlier triggers have been defence establishments and gas pipelines. A current trigger is wind turbines.

### 3 INFRASOUND AND LOW FREQUENCY NOISE FROM WIND TURBINES

Early designs of downwind turbines produced pressure pulses at about once per second, which were high enough to cause vibrations in lightweight buildings nearby. (Shepherd and Hubbard 1991). A series of pulses occurring at one per second analyses into a harmonic series in the infrasound region, which is the origin of the link between wind turbines and infrasound. One could discuss whether the Fourier time-frequency duality is misleading on this point, since it was the effects of peaks of the pulses which caused the building vibration, not a continuous infrasonic wave. Similar vibration would have occurred with a faster stream of pulses, with the limiting condition that the pulse repetition rate was lower than the period of the vibration.

Modern up-wind turbines produce pulses which also analyse as infrasound, but at low levels, typically 50 to 70dB, well below the hearing threshold. Infrasound can be neglected in the assessment of the noise of modern wind turbines (Jakobsen 2004)

Fig 2 shows the infrasonic and low frequency noise at 65m from a 1.5MW wind turbine on a windy day. The fol-

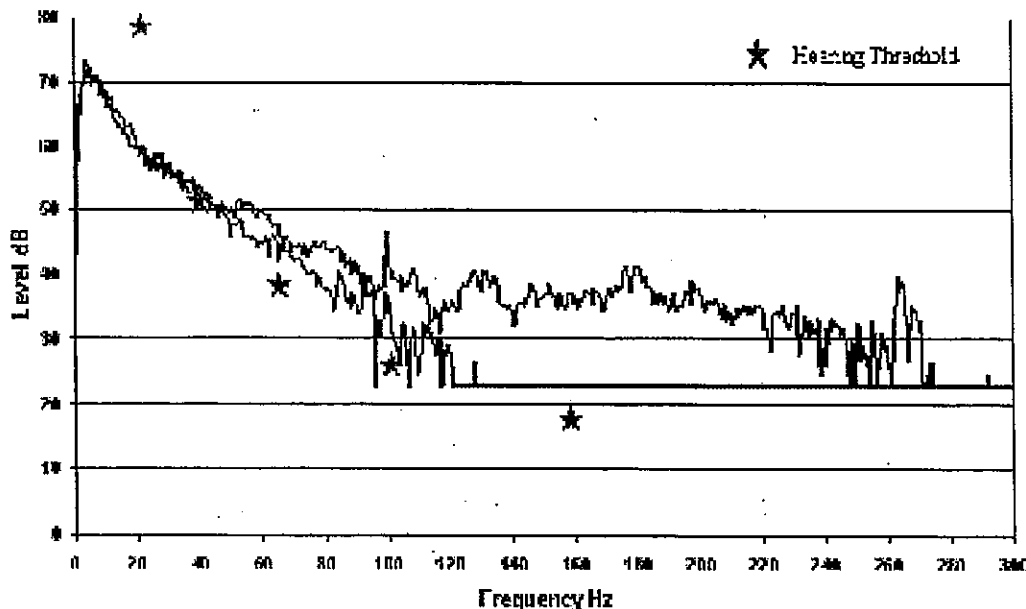


Figure 2. Spectrum of a modern upwind wind turbine - Upper trace Wind Turbine Noise. Lower trace Background noise.

lowing should be noted.

- The fall off below about 5Hz is an instrument effect. The background noise actually increases down to the frequencies of atmospheric pressure variations .
- Frequencies below 40Hz cannot be distinguished from background noise due to wind.
- The wind turbine noise and background noise separate above about 40Hz and both rise above the median hearing threshold.
- The measurements were taken at 65m. Levels are likely to be about 15dB lower at normal separation distances

On the occasions, such as unusually turbulent inflow conditions, when low frequency noise is produced by wind turbines, it may not be perceived as a noise, but rather as an unidentified adverse component in the environment, which disappears if the turbines stop, or if the inflow conditions change. This is because we are not accustomed to listening to low levels of broad band low frequency noise and, initially, do not always recognise it as a "noise", but more as a "disturbance" in the environment. An analogy is with air-conditioning rumble noise, which is noticed when it stops.

**What Objectors Say** Objectors have eagerly grasped the media hype on infrasound and low frequency noise and used it to engender concerns about wind turbine developments. In this they have, possibly, done a disservice to the communities they were established to help, through raising false concerns and diverting attention from more important aspects of the development. Two examples are as follows.

In the UK there is an Advertising Standards Authority(ASA), to which deceptive adverts can be referred for assessment. An objectors' group (Ochils Environmental Protection Group) issued a leaflet "FACTS ABOUT WIND POWER", containing a number of assertions including:

... wind turbines still create noise pollution, notably 'in-

fra sound' - inaudible frequencies which nevertheless cause stress-related illness ..."

In their Judgment (April 02, 2004), the ASA concluded that the objectors had not produced evidence to substantiate their claim.

In the USA, a high profile objector (Nina Pierpont of Malone NY) placed an advertisement in a local paper, consisting entirely of selected quotations from a previously published technical paper by van den Berg (Van den Berg 2004). However the comment "[i.e. infrasonic]", as shown in Fig 3, was added in the first line of the first quotation in a manner which might mislead naive readers into believing that it was part of the original.

The van den Berg paper was based on A-weighted measurements and had no connection with infrasound. So, not only is the advertisement displaying the advertiser's self deception, but this has also been propagated to others who have read it. To mistakenly connect the noise to infrasound, which has unpleasant associations is, however, a way to gather support. (When a person has adopted a particular mindset, new information is processed to support that mindset. We all do this.)

It takes little technical knowledge to be aware that a modulated high frequency wave does not contain the modulation components. For example, an amplitude modulated radio wave contains the carrier wave and sidebands, which are close in frequency to the carrier. The fluctuations of wind turbine noise (swish - swish) are a very low frequency modulation of the aerodynamic noise, which is typically in the region of 500 - 1000Hz. The modulation occurs from a change in radiation characteristics as the blade passes the tower, but the modulating frequencies do not have an independent and separate existence.

The comment, [ i.e. infrasonic], added into Fig 3 gives incorrect information. Claims of infrasound are irrelevant and possibly harmful, should they lead to unnecessary fears.

PAID ADVERTISEMENT

## Wind Turbines & Infrasound: What the latest research says

**"At night the wind turbines cause a low pitched thumping [i.e., infrasonic] sound superimposed on a broadband 'noisy' sound, the 'thumps' occurring at the rate at which blades pass a turbine tower.... The number and severity of noise complaints near the wind park are at least in part explained by the two main findings of this study: actual sound levels are considerably higher than predicted, and wind turbines can produce sound with an impulsive character."**

-- Professor Frits G.P. van den Berg, University of Groningen, the Netherlands, November 2004 (see excerpts from research articles, below)

Figure 3 Part of an advertisement placed by an objector in the Malone (NY) Telegram, 25th February 2005.

It has been shown that fear of a noise source, for example that aircraft might crash, increases the extra annoyance of a person with a high fear of a crash by up to 19dB DNL equivalent, compared with a person who has no fear (Miedema and Vos 1999).

Fear of a source is not the same as fear of the noise itself, but it is understandable that those who fear the effects of a noise upon their health will be less tolerant of the noise than those who do not fear it. We can only speculate upon the harm which objectors might have done by, for example, taking a one dimensional view of infrasound and publicising the subjective effects of high levels of both infrasound and low frequency noise in a manner which implies that the effects may also be caused by the low levels produced by wind turbines.

#### 4 WIND TURBINE NOISE

It has been shown above that there is insignificant infrasound from wind turbines and that there is normally little low frequency noise. Turbulent air inflow conditions cause enhanced levels of low frequency noise, which may be disturbing, but the overriding noise from wind turbines is the fluctuating audible swish, mistakenly referred to as "infrasound" or "low frequency noise". Objectors uninformed and mistaken use of these terms (as in Fig 3), which have acquired a number of anxiety-producing connotations, has led to unnecessary fears and to unnecessary costs, such as for re-measuring what was already known, in order to assuage complaints.

Attention should be focused on the audio frequency fluctuating swish, which some people may well find to be very disturbing and stressful, depending on its level. The usual equivalent level measurements and analyses are incomplete, as these measurements are taken over a time period which is much longer than the fluctuation period and information on the fluctuations is lost. A time varying sound is more annoying than a steady sound of the same average level and this is accounted for by reducing the permitted level of wind turbine noise. However, more work is required to ensure that the optimum levels have been set.

#### 5 CONCLUSIONS

- Infrasound from wind turbines is below the audible threshold and of no consequence.
- Low frequency noise is normally not a problem, except under conditions of unusually turbulent inflow air.
- The problem noise from wind turbines is the fluctuating swish. This may be mistakenly referred to as infrasound by those with a limited knowledge of acoustics, but it is entirely in the normal audio range and is typically 500Hz to 1000Hz. It is difficult to have a useful discourse with objectors whilst they continue to use acoustical terms incorrectly. This is unfortunate, as there are wind turbine installations which may have noise problems.
- It is the swish noise on which attention should be focused, in order to reduce it and to obtain a proper estimate of its

effects. It will then be the responsibility of legislators to fix the criterion levels, However, although the needs of sensitive persons may influence decisions, limits are not normally set to satisfy the most sensitive.

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*Note: Continued on Page 36*

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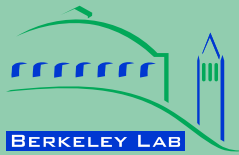
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# **The Impact of Wind Power Projects on Residential Property Values in the United States: A Multi-Site Hedonic Analysis**

**Ben Hoen, Ryan Wisler, Peter Cappers,  
Mark Thayer, and Gautam Sethi**

**Environmental Energy  
Technologies Division**

**December 2009**

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Prepared for the

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Washington, D.C.

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## **Abstract**

With wind energy expanding rapidly in the U.S. and abroad, and with an increasing number of communities considering wind power development nearby, there is an urgent need to empirically investigate common community concerns about wind project development. The concern that property values will be adversely affected by wind energy facilities is commonly put forth by stakeholders. Although this concern is not unreasonable, given property value impacts that have been found near high voltage transmission lines and other electric generation facilities, the impacts of wind energy facilities on residential property values had not previously been investigated thoroughly. The present research collected data on almost 7,500 sales of single-family homes situated within 10 miles of 24 existing wind facilities in nine different U.S. states. The conclusions of the study are drawn from eight different hedonic pricing models, as well as both repeat sales and sales volume models. The various analyses are strongly consistent in that none of the models uncovers conclusive evidence of the existence of any widespread property value impacts that might be present in communities surrounding wind energy facilities. Specifically, neither the view of the wind facilities nor the distance of the home to those facilities is found to have any consistent, measurable, and statistically significant effect on home sales prices. Although the analysis cannot dismiss the possibility that individual homes or small numbers of homes have been or could be negatively impacted, it finds that if these impacts do exist, they are either too small and/or too infrequent to result in any widespread, statistically observable impact.

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## Executive Summary

### Overview

Wind power development in the United States has expanded dramatically in recent years. If that growth is to continue it will require an ever-increasing number of wind power projects to be sited, permitted, and constructed. Most permitting processes in the U.S. require some form of environmental impact assessment as well as public involvement in the siting process. Though public opinion surveys generally show that acceptance towards wind energy is high, a variety of concerns with wind power development are often expressed on the local level during the siting and permitting process. One such concern is the potential impact of wind energy projects on the property values of nearby residences.

Concerns about the possible impact of wind power facilities on residential property values can take many forms, but can be divided into the following non-mutually exclusive categories:

- **Area Stigma:** A concern that the general area surrounding a wind energy facility will appear more developed, which may adversely affect home values in the local community regardless of whether any individual home has a view of the wind turbines.
- **Scenic Vista Stigma:** A concern that a home may be devalued because of the view of a wind energy facility, and the potential impact of that view on an otherwise scenic vista.
- **Nuisance Stigma:** A concern that factors that may occur in close proximity to wind turbines, such as sound and shadow flicker, will have a unique adverse influence on home values.

Although concerns about the possible impact of wind energy facilities on the property values of nearby homes are reasonably well established, the available literature<sup>1</sup> that has sought to quantify the impacts of wind projects on residential property values has a number of shortcomings:

- 1) Many studies have relied on surveys of homeowners or real estate professionals, rather than trying to quantify real price impacts based on market data;
- 2) Most studies have relied on simple statistical techniques that have limitations and that can be dramatically influenced by small numbers of sales transactions or survey respondents;
- 3) Most studies have used small datasets that are concentrated in only one wind project study area, making it difficult to reliably identify impacts that might apply in a variety of areas;
- 4) Many studies have not reported measurements of the statistical significance of their results, making it difficult to determine if those results are meaningful;
- 5) Many studies have concentrated on an investigation of the existence of Area Stigma, and have ignored Scenic Vista and/or Nuisance Stigmas;
- 6) Only a few studies included field visits to homes to determine wind turbine visibility and collect other important information about the home (e.g., the quality of the scenic vista); and
- 7) Only two studies have been published in peer-reviewed academic journals.

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<sup>1</sup> This literature is briefly reviewed in Section 2 of the full report, and includes: Jordal-Jorgensen (1996); Jerabek (2001); Grover (2002); Jerabek (2002); Sterzinger et al. (2003); Beck (2004); Haughton et al. (2004); Khatri (2004); DeLacy (2005); Poletti (2005); Goldman (2006); Hoen (2006); Firestone et al. (2007); Poletti (2007); Sims and Dent (2007); Bond (2008); McCann (2008); Sims et al. (2008); and Kielisch (2009).

This report builds on the previous literature that has investigated the potential impact of wind projects on residential property values by using a hedonic pricing model and by avoiding many of the shortcomings enumerated above.

The hedonic pricing model is one of the most prominent and reliable methods for identifying the marginal impacts of different housing and community characteristics on residential property values (see side bar). This approach dates to the seminal work of Rosen (1974) and Freeman (1979), and much of the available literature that has investigated the impacts of potential disamenities on property values has relied on this method.<sup>2</sup>

To seed the hedonic model with appropriate market data, this analysis collects information on a large quantity of residential home sales (i.e., transactions) ( $n = 7,459$ ) from ten communities surrounding 24 existing wind power facilities spread across multiple parts of the U.S. (e.g., nine states). Homes included in this sample are located from 800 ft to over five miles from the nearest wind energy facility, and were sold at any point from before wind facility announcement to over four years after the construction of the nearby wind project. Each of the homes that sold was visited to determine the degree to which the wind facility was likely to have been visible at the time of sale and to collect other essential data.

To assess the potential impacts of all three of the property value stigmas described earlier, a base hedonic model is applied as well as seven alternative hedonic models each designed to investigate the reliability of the results and to explore other aspects of the data (see Table ES - 1 below). In addition, a repeat sales model is analyzed, and an investigation of possible impacts on sales volumes is

### **What Is a Hedonic Pricing Model?**

Hedonic pricing models are frequently used by economists and real estate professionals to assess the impacts of house and community characteristics on property values by investigating the sales prices of homes. A house can be thought of as a bundle of characteristics (e.g., number of square feet, number of bathrooms). When a price is agreed upon by a buyer and seller there is an implicit understanding that those characteristics have value. When data from a large number of residential transactions are available, the individual marginal contribution to the sales price of each characteristic for an average home can be estimated with a hedonic regression model. Such a model can statistically estimate, for example, how much an additional bathroom adds to the sale price of an average home. A particularly useful application of the hedonic model is to value non-market goods – goods that do not have transparent and observable market prices. For this reason, the hedonic model is often used to derive value estimates of amenities such as wetlands or lake views, and disamenities such as proximity to and/or views of high-voltage transmission lines, roads, cell phone towers, and landfills. It should be emphasized that the hedonic model is not typically designed to appraise properties (i.e., to establish an estimate of the market value of a home at a specified point in time), as would be done with an automated valuation model. Instead, the typical goal of a hedonic model is to estimate the marginal contribution of individual house or community characteristics to sales prices.

---

<sup>2</sup> Many of these studies are summarized in the following reviews: Kroll and Priestley (1992); McCann (1999); Bateman et al. (2001); Boyle and Kiel (2001); Jackson (2001); Simons and Saginor (2006); and Leonard et al. (2008). For further discussion of the hedonic model and its application to the quantification of environmental stigmas see Jackson (2005) and Simons (2006a).

conducted. Though some limitations to the analysis approach and available data are acknowledged, the resulting product is the most comprehensive and data-rich analysis to date in the U.S. or abroad on the impacts of wind projects on nearby property values.

**Analysis Findings**

Table ES - 1 describes the ten resulting statistical models that are employed to investigate the effects of wind facilities on residential sales prices, and the specific stigmas that those models investigate. Though all models test some combination of the three possible stigmas, they do so in different ways. For instance, the Base Model asks the question, “All else being equal, do homes near wind facilities sell for prices different than for homes located farther away?”, while the All Sales Model asks, “All else being equal, do homes near wind facilities that sell after the construction of the wind facility sell for prices different from similar homes that sold before the announcement and construction of the facility?” Each model is therefore designed to not only test for the reliability of the overall results, but also to explore the myriad of potential effects from a variety of perspectives. Table ES-2 summarizes the results from these models.

**Table ES - 1: Description of Statistical Models**

<b>Statistical Model</b>	<b>Description</b>
<b>Base Hedonic Model</b>	Using only "post-construction" transactions (those that occurred after the wind facility was built), this model investigates all three stigmas in a straightforward manner
<b>Alternative Hedonic Models</b>	
View Stability	Using only post-construction transactions, this model investigates whether the Scenic Vista Stigma results from the Base Model are independent of the Nuisance and Area Stigma results
Distance Stability	Using only post-construction transactions, this model investigates whether the Nuisance and Area Stigma results from the Base Model are independent of the Scenic Vista Stigma results
Continuous Distance	Using only post-construction transactions, this model investigates Area and Nuisance Stigmas by applying a continuous distance parameter as opposed to the categorical variables for distance used in the previous models
All Sales	Using all transactions, this model investigates whether the results for the three stigmas change if transactions that occurred before the announcement and construction of the wind facility are included in the sample
Temporal Aspects	Using all transactions, this model further investigates Area and Nuisance Stigmas and how they change for homes that sold more than two years pre-announcement through the period more than four years post-construction
Orientation	Using only post-construction transactions, this model investigates the degree to which a home’s orientation to the view of wind turbines affects sales prices
Overlap	Using only post-construction transactions, this model investigates the degree to which the overlap between the view of a wind facility and a home’s primary scenic vista affects sales prices
<b>Repeat Sales Model</b>	Using paired transactions of homes that sold once pre-announcement and again post-construction, this model investigates the three stigmas, using as a reference transactions of homes located outside of five miles of the nearest wind turbine and that have no view of the turbines
<b>Sales Volume Model</b>	Using both pre-announcement and post-construction transactions, this model investigates whether the rate of home sales (not the price of those sales) is affected by the presence of nearby wind facilities

**Table ES-2: Impact of Wind Projects on Property Values: Summary of Key Results**

Statistical Model	Is there statistical evidence of:			Section Reference
	Area Stigma?	Scenic Vista Stigma?	Nuisance Stigma?	
Base Model	No	No	No	Section 4
View Stability	Not tested	No	Not tested	Section 5.1
Distance Stability	No	Not tested	No	Section 5.1
Continuous Distance	No	No	No	Section 5.2
All Sales	No	No	Limited	Section 5.3
Temporal Aspects	No	No	No	Section 5.4
Orientation	No	No	No	Section 5.5
Overlap	No	Limited	No	Section 5.6
Repeat Sales	No	Limited	No	Section 6
Sales Volume	No	Not tested	No	Section 7

"No"..... No statistical evidence of a negative impact  
 "Yes"..... Strong statistical evidence of a negative impact  
 "Limited"..... Limited and inconsistent statistical evidence of a negative impact  
 "Not tested"..... This model did not test for this stigma

**Base Model Results**

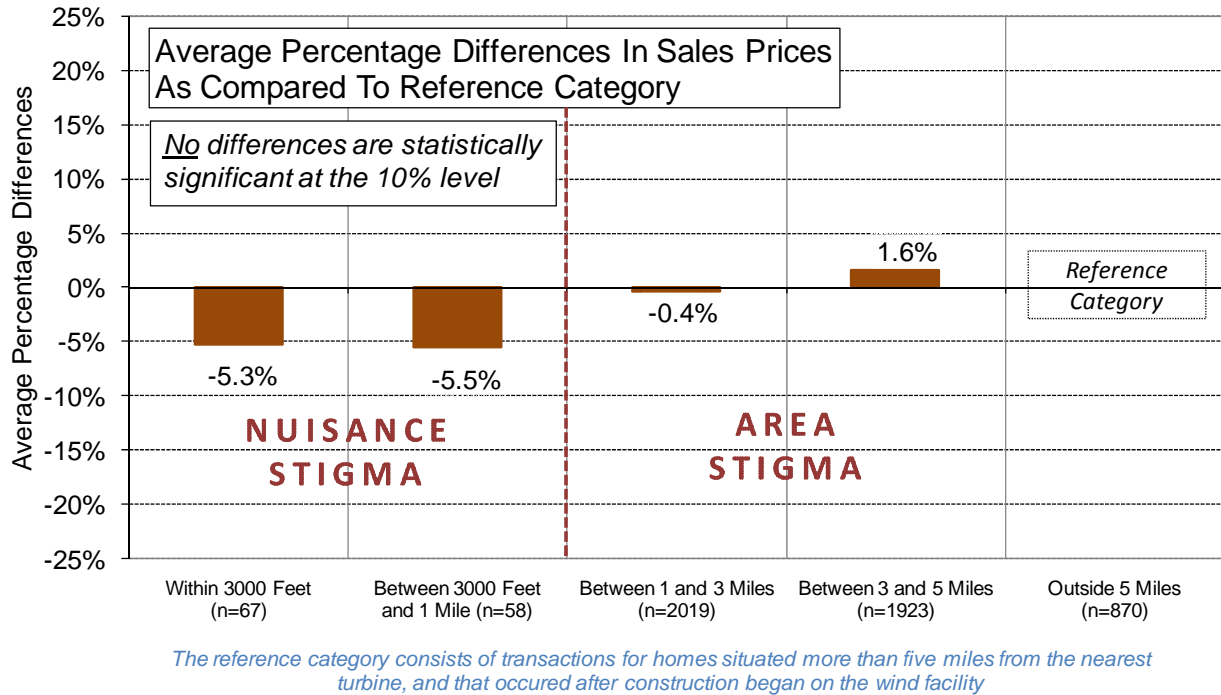
The Base Model serves as the primary model and allows all three stigmas to be explored. In sum, this model finds no persuasive evidence of any of the three potential stigmas: neither the view of the wind facilities nor the distance of the home to those facilities is found to have any consistent, measurable, and statistically significant effect on home sales prices.

- **Area Stigma:** To investigate Area Stigma, the model tests whether the sales prices of homes situated anywhere outside of one mile and inside of five miles of the nearest wind facility are measurably different from the sales price of those homes located outside of five miles. No statistically significant differences in sales prices between these homes are found (see Figure ES-1).
- **Scenic Vista Stigma:** For Scenic Vista Stigma, the model is first used to investigate whether the sales prices of homes with varying scenic vistas - absent the presence of the wind facility - are measurably different. The model results show dramatic and statistically significant differences in this instance (see Figure ES-2); not surprisingly, home buyers and sellers consider the scenic vista of a home when establishing the appropriate sales price. Nonetheless, when the model tests for whether homes with minor, moderate, substantial, or extreme views of wind turbines have measurably different sales prices, no statistically significant differences are apparent (see Figure ES-3).
- **Nuisance Stigma:** Finally, for Nuisance Stigma, the model is used to test whether the sales prices of homes situated inside of one mile of the nearest wind energy facility are measurably different from those homes located outside of five miles. Although sample size is somewhat limited in this case,<sup>3</sup> the model again finds no persuasive statistical evidence that wind

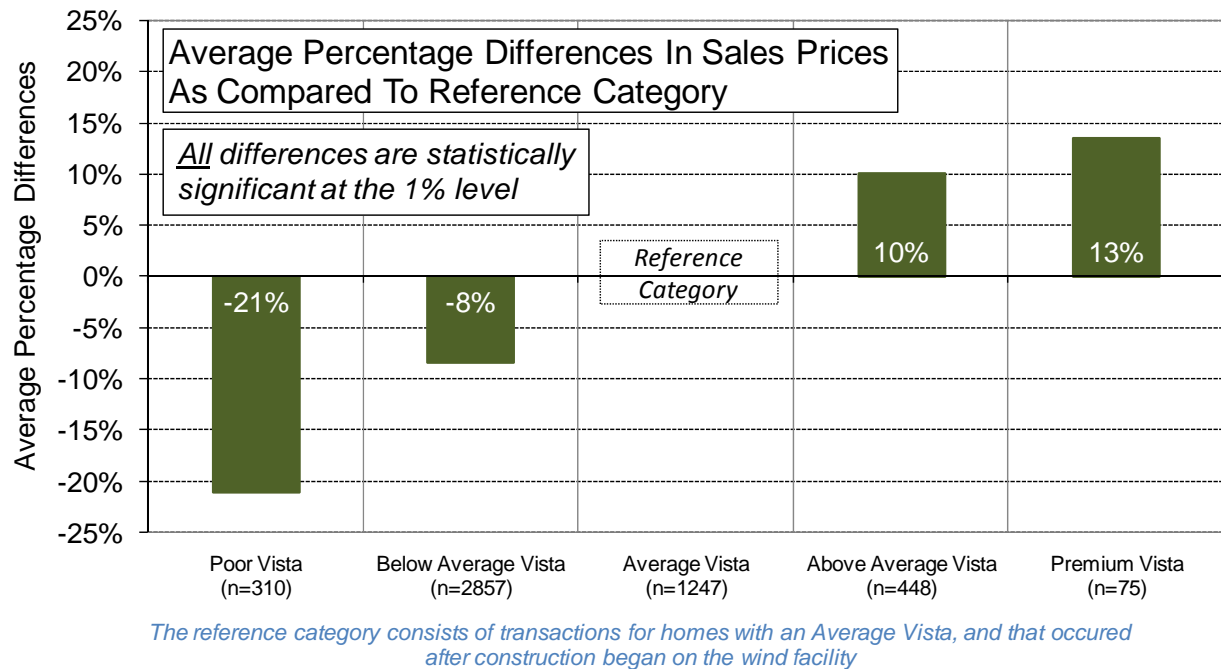
<sup>3</sup> 125 homes were located inside of one mile of the nearest wind facility and sold post-construction.

facilities measurably and broadly impact residential sales prices (see Figure ES-1 and later results).

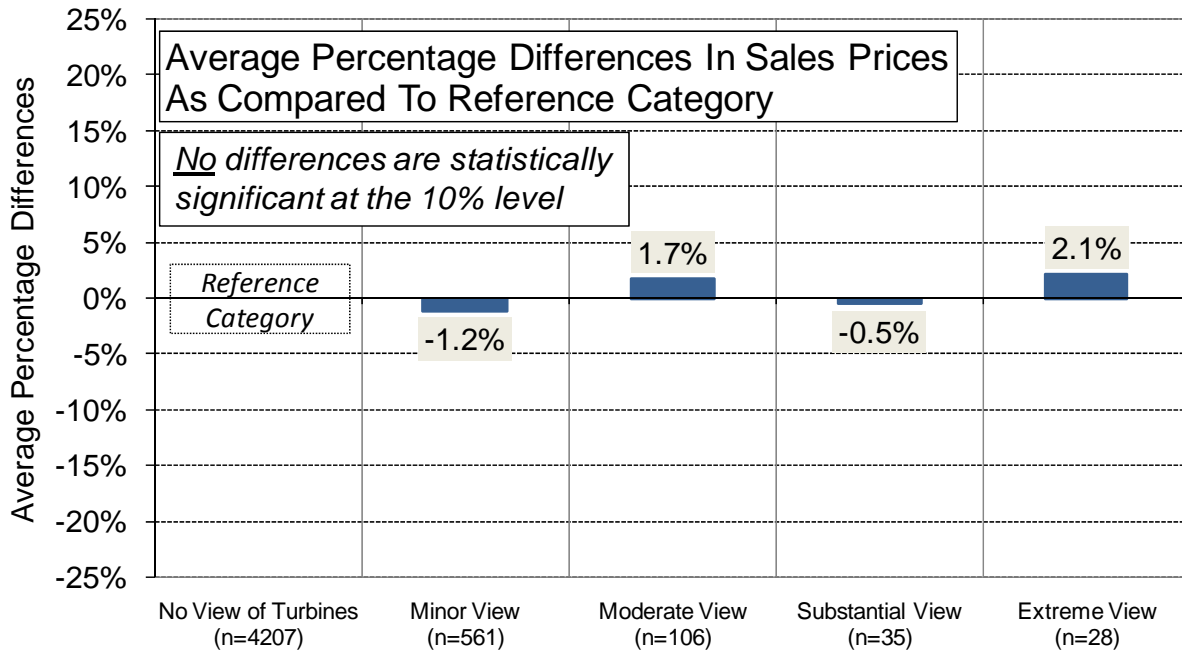
**Figure ES-1: Base Model Results: Area and Nuisance Stigma**



**Figure ES-2: Base Model Results: Scenic Vista**



**Figure ES-3: Base Model Results: Scenic Vista Stigma**



*The reference category consists of transactions for homes without a view of the turbines, and that occurred after construction began on the wind facility*

The seven alternative hedonic models and the additional analysis contained in the Repeat Sales and Sales Volume Models (see Table ES-2) provide a fuller picture of the three stigmas and the robustness of the Base Model results.

**Area Stigma: Other Model Results**

Concentrating first on Area Stigma, the results from all of the models are similar: there is no statistical evidence of a widespread Area Stigma among the homes in this sample. Homes in the study areas analyzed here do not appear to be measurably stigmatized by the arrival of a wind facility, regardless of when those homes sold in the wind project development process and regardless of whether the homes are located one mile or five miles away from the nearest facility.

In the All Sales Model, for example, after adjusting for inflation,<sup>4</sup> homes that sold after wind facility construction and that had no view of the turbines are found to have transacted for higher prices - not lower - than those homes that sold prior to wind facility construction. Moreover, in the Temporal Aspects Model, homes that sold more than two years prior to the announcement of the wind facility and that were located more than five miles from where the turbines were eventually located are found to have transacted for lower prices - not higher - than homes situated closer to the turbines and that sold at any time after the announcement and construction of the wind facility (see Figure ES - 4). Further, in the Repeat Sales Model, homes located near the wind facilities that transacted more than once were found to have appreciated between those sales by an amount that was no different from that experienced by homes located in an area

<sup>4</sup> All sales prices in all models are adjusted for inflation, but because this model (and the Temporal Aspects Model) deals with time explicitly, it is mentioned specifically here.



many miles away from the wind facilities. Finally, as shown in Table ES-2, none of the other models identified evidence of a broadly negative and statistically significant Area Stigma.

### ***Scenic Vista Stigma: Other Model Results***

With respect to Scenic Vista Stigma, the seven alternative hedonic models and the additional analysis contained in the Repeat Sales Model find little consistent evidence of a broadly negative and statistically significant impact. Although there are 730 residential transactions in the sample that involve homes that had views of a wind facility at the time of sale, 160 of which had relatively significant views (i.e., a rating higher than Minor), none of the various models finds strong statistical evidence that the view of a nearby wind facility impacts sales prices in a significant and consistent manner.

When concentrating only on the view of the wind facilities from a home (and not testing for Area and Nuisance Stigmas simultaneously), for example, the results from the View Stability Model are very similar to those derived from the Base Model, with no evidence of a Scenic Vista Stigma. Similarly, the All Sales Model finds that homes that sold after wind facility construction and that had a view of the facility transacted for prices that are statistically indistinguishable from those homes that sold at any time prior to wind facility construction. The Orientation Model, meanwhile, fails to detect any difference between the sales prices of homes that had either a front, back, or side orientation to the view of the wind facility. As shown in Table ES-2, the Continuous Distance and Temporal Aspects models also do not uncover any evidence of a broadly negative and statistically significant Scenic Vista Stigma.

In the Repeat Sales Model, some limited evidence is found that a Scenic Vista Stigma may exist, but those effects are weak, fairly small, somewhat counter-intuitive, and are at odds with the results of other models. This finding is likely driven by the small number of sales pairs that are located within one mile of the wind turbines and that experience a dramatic view of those turbines. Finally, in the Overlap Model, where the degree to which a view of the wind facility overlaps the primary scenic vista from the home is accounted for, no statistically significant differences in sales prices are detected between homes with somewhat or strongly overlapping views when compared to those homes with wind turbine views that did not overlap the primary scenic vista. Though this model produces some weak evidence of a Scenic Vista Stigma among homes with Minor views of wind facilities, the same model finds that the sales prices of those homes with views that barely overlap the primary scenic vista are positively impacted by the presence of the wind facility. When these two results are combined, the overall impact is negligible, again demonstrating no persuasive evidence of a Scenic Vista Stigma.

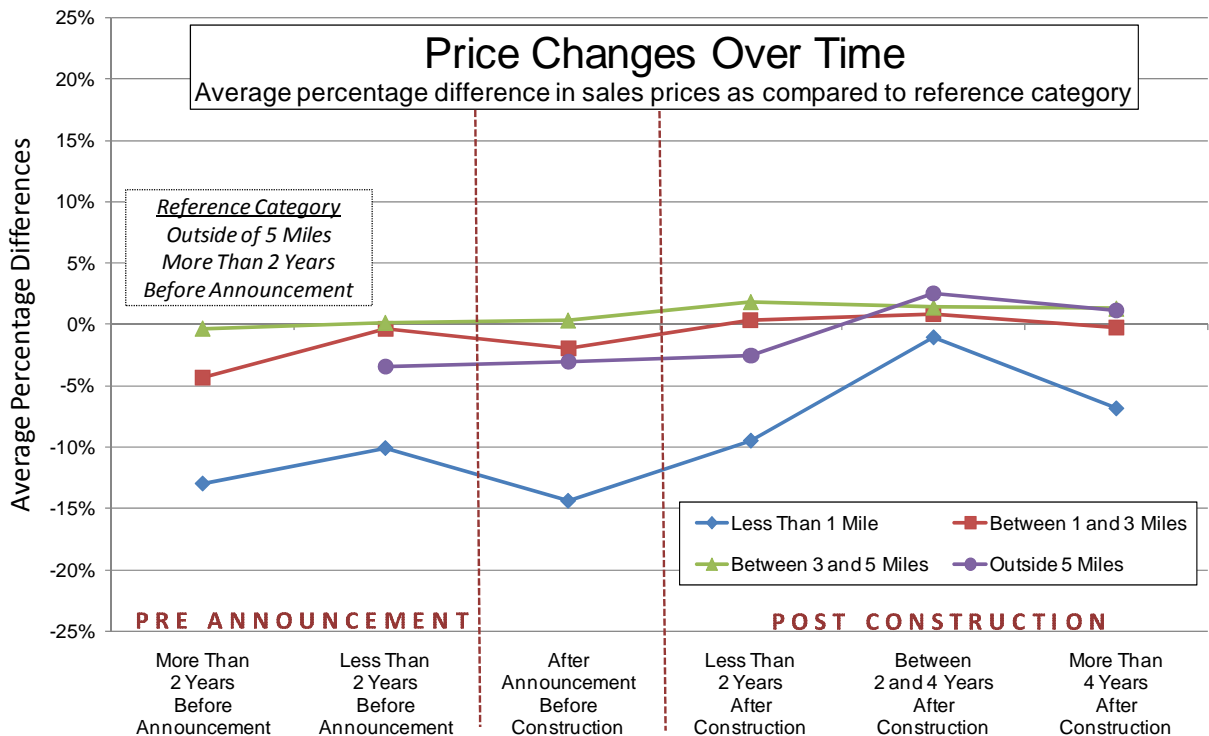
### ***Nuisance Stigma: Other Model Results***

Results for Nuisance Stigma from the seven alternative hedonic models and the additional analysis contained in the Repeat Sales and Sales Volume Models support the Base Model results. Taken together, these models present a consistent set of results: homes in this sample that are within a mile of the nearest wind facility, where various nuisance effects have been posited, have not been broadly and measurably affected by the presence of those wind facilities. These results imply that Nuisance Stigma effects are either not present in this sample, or are too small and/or infrequent to be statistically distinguished.

In the Distance Stability Model, for example, when concentrating only on the distance from homes to the nearest wind turbine (and not testing for Scenic Vista Stigma simultaneously), the results are very similar to those derived from the Base Model, with no statistical evidence of a Nuisance Stigma. These results are corroborated by the Continuous Distance, Orientation, Overlap, and Repeat Sales Models, none of which find a statistically significant relationship between distance and either sales prices or appreciation rates. Relatedly, the Sales Volume analysis finds no evidence that homes located within one mile of the nearest wind turbine are sold any more or less frequently than homes located farther away from the wind facilities.

In the All Sales Model, a weakly significant difference is found between the sales prices of homes located between 3000 feet and one mile of the nearest wind facility and the homes that sold before the announcement of the wind facility. This effect, however, is largely explained by the results of the Temporal Aspects Model, shown in Figure ES - 4. The Temporal Aspects Model finds that homes located within one mile of where the wind turbines would eventually be located sold for depressed prices well before the wind facility was even announced or constructed. In all time periods following the commencement of wind facility construction, however, inflation-adjusted sales prices increased - not decreased - relative to pre-announcement levels, demonstrating no statistical evidence of a Nuisance Stigma. The results from the All Sales Model (and, for that matter, the negative, albeit statistically insignificant coefficients inside of one mile in the Base Model, see Figure ES-1) are therefore an indication of sales price levels that preceded wind facility announcement construction, and that are not sustained after construction.

**Figure ES - 4: Temporal Aspects Model Results: Area and Nuisance Stigma**



*The reference category consists of transactions of homes situated more than five miles from where the nearest turbine would eventually be located and that occurred more than two years before announcement of the facility*

### **Conclusions and Further Research Needs**

Though each of the analysis techniques used in this report has strengths and weaknesses, the results as a whole are strongly consistent in that none of the models uncovers conclusive evidence of the presence of any of the three property value stigmas that might be present in communities surrounding wind power facilities. Therefore, based on the data sample and analysis presented here, no evidence is found that home prices surrounding wind facilities are consistently, measurably, and significantly affected by either the view of wind facilities or the distance of the home to those facilities. Although the analysis cannot dismiss the possibility that individual homes or small numbers of homes have been or could be negatively impacted, it finds that if these impacts do exist, they are either too small and/or too infrequent to result in any widespread, statistically observable impact. Moreover, to the degree that homes and wind facilities in this sample are similar to homes and facilities in other areas of the United States, the results presented here are expected to be transferable to other areas.

This work builds on the existing literature in a number of respects, but there remain a number of areas for further research. The primary goal of subsequent research should be to concentrate on those homes located closest to wind facilities, where the data sample herein was the most limited. Additional research of the nature reported in this paper could be pursued, but with a greater number of transactions, especially for homes particularly close to wind facilities. A more detailed analysis of sales volume impacts may also be fruitful, as would an assessment of the potential impact of wind facilities on the length of time homes are on the market in advance of an eventual sale. Finally, it would be useful to conduct a survey of those homeowners living close to existing wind facilities, and especially those residents who have bought and sold homes in proximity to wind facilities after facility construction, to assess their opinions on the impacts of wind project development on their home purchase and sales decisions.

# 1. Introduction

Wind power development has expanded dramatically in recent years (GWEC, 2009). Although the percent of electricity supplied to the U.S. and globally from wind power projects installed through 2008 remains relatively low (1.9% and 1.5%, respectively) (Wiser and Bolinger, 2009), there are expectations that those percentages will rise and that wind energy could contribute a significant percentage of future electricity supply (GWEC, 2008; Wiser and Hand, 2010). Most recently, President Obama, in his 2009 State of the Union address, called for a doubling of renewable energy in three years (by 2012), and in 2008 the U.S. Department of Energy produced a report that analyzed the feasibility of meeting 20% of U.S. electricity demand with wind energy by 2030 (US DOE, 2008).

To meet these goals, a significant amount of wind project development activity would be required. The average size of wind power projects built in the U.S. in 2007 and 2008 was approximately 100 MW (Wiser and Bolinger, 2009) and the total amount of capacity required to reach 20% wind electricity is roughly 300,000 MW (US DOE, 2008). Therefore, to achieve 20% wind electricity by 2030, a total of 3,000 wind facilities may need to be sited and permitted. Most permitting processes in the U.S. require some form of environmental impact assessment, and some form of public involvement in the siting process. Though surveys show that public acceptance is high in general for wind energy (e.g., Wolsink, 2000; Firestone and Kempton, 2006), a variety of concerns are often expressed on the local level that can impact the length and outcome of the siting and permitting process. These concerns range from the potential impacts of wind projects on wildlife habitat and mortality, radar and communications systems, ground transportation and historic and cultural resources, to aesthetic and property value concerns as well as potential nuisance and health impacts. As a result, a variety of siting and permitting guidelines (AWEA, 2008) and impact assessments (NAS, 2007) have been completed.

Surveys of local communities considering wind facilities have consistently ranked adverse impacts on aesthetics and property values in the top tier of concerns (e.g., BBC R&C, 2005; Firestone and Kempton, 2006). Developers of wind energy echo this assessment: they ranked aesthetics and property values as two of the top concerns (first and third respectively) for individuals or communities opposed to wind power development (Paul, 2006). Local residents have even brought suit against a developer over property values (Dale Rankin v. FPL, 2008), and some developers have responded to these concerns by offering “neighbor agreements” that compensate nearby homeowners for the potential impacts of wind projects.

The two concerns of aesthetics and property values are intrinsically linked. It is well established that a home’s value will be increased if a high-quality scenic vista is enjoyed from the property (e.g., Seiler et al., 2001). Alternatively, it is reasonable to assume that if a home’s scenic vista overlaps with a view of a disamenity, the home might be devalued, as has been found for high-voltage transmission lines (HVTL) (Kroll and Priestley, 1992; Des-Rosiers, 2002). Whether a view of wind turbines similarly impacts home values is a key topic of debate in local siting decisions. Aesthetics alone, however, is not the only pathway through which wind projects might impact residential property values. Distance to the nearest wind turbine, for example, might also have an impact if various nuisance effects are prominent, such as turbine noise,

shadow flicker,<sup>5</sup> health or safety concerns, or other impacts, real or perceived. In this way, property values near wind turbines might be impacted in the same way as homes near roads might be devalued (Bateman et al., 2001). Additionally, there is evidence that proximity to a disamenity, even if that disamenity is not visible and is not so close as to have obvious nuisance effects, may still decrease a home's sales price, as has been found to be the case for landfills (Thayer et al., 1992).

Taken together, these general concerns about the possible impacts of wind projects on residential property values can be loosely categorized into three potential stigmas:

- **Area Stigma:** A concern that the general area surrounding a wind energy facility will appear more developed, which may adversely affect home values in the local community regardless of whether any individual home has a view of the wind turbines.
- **Scenic Vista Stigma:** A concern that a home may be devalued because of the view of a wind energy facility, and the potential impact of that view on an otherwise scenic vista.
- **Nuisance Stigma:** A concern that factors that may occur in close proximity to wind turbines, such as sound and shadow flicker, will have a unique adverse influence on home values.

These three potential stigmas are not mutually exclusive and could, in theory, be present in part or in combination for any single home. Consequently, all three potential impacts must be considered when analyzing the effects of wind facilities on residential sales prices.

Although concerns about the potential impact of wind projects on residential property values are often mentioned in siting cases, the state of the existing literature on this topic leaves much to be desired. To some extent, the growing body of research investigating this topic has come to opposing conclusions. The most recent and comprehensive of these studies have often concluded that no widespread impacts of wind projects on residential property values are apparent (Hoen, 2006; Sims and Dent, 2007; Sims et al., 2008). At the same time, pre-construction surveys of both homeowners and real estate experts have sometimes found an expectation of negative impacts (e.g. Haughton et al., 2004), and post-construction appraisals have sometimes come to similar conclusions (McCann, 2008; Kielisch, 2009). Given the state of the literature, it is not uncommon for local siting and permitting processes to involve contradicting testimony from experts, as occurred in 2004 when the Public Service Commission of Wisconsin heard opposing conclusions from two studies conducted by experienced home valuation experts (Poletti, 2005; Zarem, 2005).

This report contains the most comprehensive and data-rich analysis to date on the potential impacts of wind projects on nearby residential sales prices. Data from 7,459 residential transactions were collected from the surrounding communities of 24 individual wind projects in nine states and 14 counties in the United States.<sup>6</sup> Because of the large sample size, the diversity of wind projects included in the analysis, and the depth of information collected, a number of different analyses were possible. Specifically, this report relies heavily on a hedonic regression

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<sup>5</sup> Shadow flicker occurs when the sun shines through the wind turbine blades when at a low angle to the horizon and shadows are cast on a window or interior wall of a residence (NAS, 2007).

<sup>6</sup> The majority of the analysis only includes homes that sold after wind facility construction began, totaling 4,937 transactions.

model<sup>7</sup> and uses various forms of that model to investigate potential effects and to confirm the robustness of the resulting findings. To further investigate the robustness of the results, a repeat sales model<sup>8</sup> and a sales volume model<sup>9</sup> are also utilized. In sum, this work builds and improves on the previous literature, and provides an in-depth assessment of the question of whether residential property values in the United States have been affected, in a statistically measurable way, by views of and proximity to wind power facilities.

The remainder of this report is structured as follows. The next section discusses the hedonic model in general, its application to environmental disamenities research, and some potentially analogous results drawn from these studies. This is followed by a summary of the existing literature that has investigated the effects of wind energy on residential property values. The report then turns to the data used in the analysis, a discussion of the primary (or “base”) hedonic model, and an analysis of the results from that statistical model. Following that, a set of alternative hedonic models are estimated, as well as a repeat sales model and sales volume model, to test for the robustness of the “base” model results and to explore other aspects of the data. Taking into account the full set of results presented earlier, the report then discusses the three stigmas that may lead to wind projects impacting residential property values, and summarizes how the analysis informs the existence and magnitude of these potential effects. The report ends with a brief conclusion, and a discussion of future research possibilities. A number of appendices follow the conclusion, and contain detailed information on each wind project study area, the data collection instrument and qualitative rating systems used in the field research, the investigation of the best “base” model, the hedonic model assumptions and related tests, and full results from all of the additional statistical models estimated in the report.

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<sup>7</sup> The hedonic regression model, which was briefly described in a sidebar in the Executive Summary, is described in detail in Section 2.1.

<sup>8</sup> A repeat sales model uses, as its dataset, only those homes that have sold more than once. By comparing annual appreciation rates of homes that sold once before facility announcement, and again after construction, it can be tested, in an alternative fashion, if home values are affected by the distance to or view of nearby wind turbines.

<sup>9</sup> Sales volume can be defined as the percentage of homes that fit a certain criteria (e.g. single family, on less than 25 acres, zoned residential, assessed for more than \$10,000) that actually did sell. By comparing sales volumes at various distances to wind facilities, before and after the facility was built, a further robustness test is possible.

## 2. Previous Research

Hedonic pricing models are frequently used to assess the marginal impacts of house and community characteristics on sales prices and by extension on property values in general. Because the hedonic model is the primary statistical method used in this report, this section begins by describing the model in more detail and providing some relevant examples of its use. The section then reviews the existing literature on the effects of wind energy facilities on surrounding property values, highlights the shortcomings of that literature, and outlines how the present research addresses those shortcomings.

### 2.1. Hedonic Models and Environmental Disamenities

A house can be thought of as a bundle of characteristics (e.g., number of square feet, number of bathrooms, number of fireplaces, and amount of acreage). When a price is agreed upon between a buyer and seller there is an implicit understanding that those characteristics have value. When data from a number of sales transactions are available, the individual marginal contribution to the sales price of each characteristic can be estimated with a hedonic regression model (Rosen, 1974; Freeman, 1979). This relationship takes the basic form:

Sales price =  $f$  (house structural characteristics, other factors)

where “house structural characteristics” might include, but are not limited to, the number of square feet of living area, bathrooms, and fireplaces, the presence of central AC and the condition of the home, and “other factors” might include, but are not limited to, home site characteristics (e.g., number of acres), neighborhood characteristics (e.g., school district), market conditions at the time of sale (e.g., prevailing mortgage interest rates), and surrounding environmental conditions (e.g., proximity to a disamenity or amenity).

The relationship between the sales price of homes and the house characteristics and other factors can take various forms. The most common functional form is the semi-log construction where the dependent variable is the natural log of the inflation adjusted sales price, and the independent variables are unadjusted (not transformed) home characteristics and other factors. The usefulness of this form of hedonic model is well established (Malpezzi, 2003; Sirmans et al., 2005b; Simons and Saginor, 2006) assuming that certain threshold assumptions are met.<sup>10</sup> The model is used commonly by academics, real estate assessors, appraisers, and realtors when large datasets are available on past residential sales transactions, and when estimates of the marginal impact of certain house characteristics and other factors on sales prices are desired.<sup>11</sup>

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<sup>10</sup> These assumptions, which are discussed in greater detail in Section 4.2 and Appendix G, include absence of outliers and/or influencers, presence of homoskedastic variances, absence of spatial and temporal autocorrelation, and absence of collinearity between the variables of interest and other independent variables.

<sup>11</sup> It should be emphasized that a hedonic model is not designed to appraise properties (i.e., to establish an estimate of the market value of a home at a specified point in time), as would be done with an automated valuation model (AVM). Rather, hedonic models are designed to estimate the marginal contribution of individual house or community characteristics to sales prices, which requires hedonic models to rely upon large data sets with a sizable number of explanatory variables. Appraisal models, on the other hand, are generally based on small, localized data sets (i.e., “comps”) and a limited number of explanatory variables that pertain to nearby properties. Due to their higher level of accuracy through the use of significantly more information (e.g., diverse spatial, temporal, and

A particularly useful application of the hedonic regression model is to value non-market goods – goods that do not have transparent and observable market prices. For this reason, the hedonic model is often used to derive value estimates of amenities such as wetlands (e.g., Mahan et al., 2000) or lake views (e.g., Seiler et al., 2001), and disamenities, such as proximity to and/or views of high-voltage transmission lines (HVTLs) (e.g. Des-Rosiers, 2002), fossil fuel power plants (Davis, 2008), roads (e.g. Bateman et al., 2001), cell phone towers (e.g. Bond and Wang, 2007), and landfills (e.g., Thayer et al., 1992; Ready and Abdalla, 2005).

There are a number of useful reviews that describe the application of hedonic models in these circumstances (Kroll and Priestley, 1992; Farber, 1998; McCann, 1999; Bateman et al., 2001; Boyle and Kiel, 2001; Jackson, 2001; Ready and Abdalla, 2005; Simons and Saginor, 2006; Simons, 2006b; Leonard et al., 2008).<sup>12</sup> The large number of studies covered in these reviews demonstrate that hedonic models are regularly used to investigate the interplay between home values and distance to potential disamenities, teasing out if and how sales prices are adversely affected depending on the distance of a typical home from a disamenity. For example, Carroll et al. (1996) use a hedonic model to estimate a devaluation of 16% for homes “close to” a chemical plant, with a 6.5% increase in sales price per mile away out to 2.5 miles, at which point effects fade entirely. Dale et al. (1999) find a maximum effect of -4% near a lead smelter, with sales prices increasing 2% for each mile away out to two miles, where effects again fade. Ready and Abdalla (2005) find maximum effects near landfills of -12.4%, which fade entirely outside 2,400 feet, and maximum effects near confined animal feeding operations of -6.4%, which fade entirely outside of 1,600 feet. Meanwhile, studies of other energy infrastructure, such as HVTLs, find maximum effects of -5.7% for homes adjacent to a HVTL tower, and an increase in prices of 0.018% per foot away from the tower out to 300 feet (Hamilton and Schwann, 1995), and maximum effects of -14% for homes within 50 feet of a HVTL, but no effect for similar homes at 150 feet (Des-Rosiers, 2002). Further, for fossil fuel power plants, Davis (2008) finds average adverse effects of between 3 and 5% inside of two miles but that those effects fade entirely outside of that distance range.

In addition to investigating how sales prices change with distance to a disamenity, hedonic models have been used to investigate how prices have changed over time. For instance, sales prices have sometimes been found to rebound after the removal of a disamenity, such as a lead smelter (Dale et al., 1999), or to fade over time, as with HVTLs (Kroll and Priestley, 1992) or spent fuel storage facilities (Clark and Allison, 1999). Finally, hedonic models have been used to estimate how views of a disamenity affect sales prices. Des-Rosiers (2002), for example, finds that homes adjacent to a power line and facing a HVTL tower sell for as much as 20% less than similar homes that are not facing a HVTL tower.

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characteristic information) and rigorous methodology, hedonic models can also be used as appraisal models. Automated valuation models cannot, however, be reliably used to measure marginal effects because they do not employ sufficient information to do so, and, more importantly, AVMs do not hold controlling characteristics constant, which could bias any resulting estimates of marginal effects.

<sup>12</sup> For further discussion of the hedonic model and its application to the quantification of environmental stigmas in comparison to other methods see Jackson (2005).



It is unclear how well the existing hedonic literature on other disamenities applies to wind turbines, but there are likely some similarities. For instance, in general, the existing literature seems to suggest that concerns about lasting health effects provide the largest diminution in sales prices, followed by concerns for one's enjoyment of the property, such as auditory and visual nuisances, and that all effects tend to fade with distance to the disamenity - as the perturbation becomes less annoying. This might indicate that property value effects from wind turbines are likely to be the most pronounced quite close to them, but fade quickly as their auditory and visual impacts fade. The existing hedonic literature also, in general, finds that effects fade with time as self-selecting buyers without prejudice towards the disamenity move into the area, or as the real or perceived risks of the disamenity are lessened (Jackson, 2001). This implies that any stigmas related to wind turbines might also fade over time as local communities come to accept their presence.

## **2.2. Impacts of Wind Projects on Property Values**

Turning to the literature that has investigated the potential property value effects from wind facilities directly, it deserves note that few studies have been academically peer-reviewed and published; in some cases, the work has been performed for a party on one side or the other of the permitting process (e.g., the wind developer or an opposition group). Nonetheless, at a minimum, a brief review of this existing literature will set the stage for and motivate the later discussion of the methods and results of the present work. The literature described below is summarized in Table 1. To frame this discussion, where possible, the three potential stigmas discussed earlier are used:

- **Area Stigma:** A concern that the general area surrounding a wind energy facility will appear more developed, which may adversely affect home values in the local community regardless of whether any individual home has a view of the wind turbines.
- **Scenic Vista Stigma:** A concern that a home may be devalued because of the view of a wind energy facility, and the potential impact of that view on an otherwise scenic vista.
- **Nuisance Stigma:** A concern that factors that may occur in close proximity to wind turbines, such as sound and shadow flicker, will have a unique adverse influence on home values.

In one of the most recent studies, Sims et al. (2008) used a hedonic model to investigate Scenic Vista Stigma using 199 residential transactions within ¼ of a mile of the 16-turbine Bears Down wind facility in Cornwall, UK. They found both large positive and smaller negative significant relationships between views of the turbines and sales prices depending on whether the view is seen from the front or rear of the home, respectively, but found no relationship between the number of wind turbines visible and sales prices. Previously, Sims and Dent (2007) used a hedonic model to investigate Nuisance and Scenic Vista Stigma with 919 transactions for homes within five miles of two wind facilities in the UK, finding only limited evidence of a relationship between proximity to and views of turbines and sales prices, which local real estate experts attributed to other causes. Hoen (2006) investigated Scenic Vista Stigma using a hedonic model to analyze 280 residential transactions occurring near a wind facility in Madison County, NY, and found no evidence that views of turbines significantly affects prices. Jordal-Jorgensen (1996) investigated Nuisance Stigma in Denmark, and found an adverse effect for homes located “close” to the turbines, but no statistical significance was reported.<sup>13</sup>

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<sup>13</sup> A copy of this report could not be obtained and therefore its findings are reported based on other citations.

Using different statistical methods, Poletti (2005; 2007) used a *t*-Test to investigate Nuisance and Area Stigma by comparing the mean sales prices of 187 and 256 homes in Illinois and Wisconsin, respectively, located near wind facilities (target group) to those further away (control group).<sup>14, 15</sup> He split these target and control groups into respective smaller and more-homogenous sub-groups, such as large and small tracts, with and without homes, finding no statistical evidence that homes near the wind facilities sold for different prices than those farther away. Sterzinger et al. (2003) analyzed roughly 24,000 residential transactions, which were divided between those within five miles of a wind facility and those outside of five miles in an effort to assess Area Stigma. They compared residential appreciation rates over time, and found no apparent difference between those homes within and outside of five miles from a wind facility, but the statistical significance of this comparison was not reported.

Other authors have used smaller samples of residential transactions and a variety of simple statistical techniques, without reporting statistical significance, and have found a lack of evidence of effects from Nuisance Stigma (Jerabek, 2001; Jerabek, 2002; Beck, 2004) and Area Stigma (DeLacy, 2005; Goldman, 2006). These results, however, are somewhat contrary to what one appraiser has found. In his investigation of Nuisance Stigma around a wind facility in Lee County, IL, McCann (2008) found that two homes nearby a wind facility had lengthy selling periods that, he believes, also adversely affected transaction prices. Additionally, Kielisch (2009) investigated Nuisance Stigma by comparing twelve transactions of undeveloped land near two wind facilities in Wisconsin (Blue Sky Green Field and Forward) to undeveloped land transactions farther away. He found that land tracts near the wind facilities sold for dramatically lower prices (\$/acre) than the comparable group, but the statistical significance of the comparison was not reported.

In addition to these revealed preference studies, a number of stated preference surveys (e.g., contingent valuation) and general opinion surveys have investigated the existence of potential effects.<sup>16</sup> A survey of local residents, conducted after the wind facilities were erected, found no evidence of Area Stigma (Goldman, 2006), while another found limited evidence of these stigmas (Bond, 2008).<sup>17</sup> Similarly, some surveys of real estate experts conducted after facility

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<sup>14</sup> A *t*-Test is used to compare two sample means by discerning if one is significantly different from the other.

<sup>15</sup> The 2007 study used the data contained in the 2005 study in combination with new data consisting of transactions that occurred in the interim period.

<sup>16</sup> Contingent valuation is a survey based technique to value non-market goods (e.g., an environmental disamenity) that asks respondents what their “willingness to pay” (or “willingness to accept”) is to have, for instance, a disamenity removed from (or to have it remain in) their neighborhood. This technique is distinct from a general opinion survey, which might ask whether respondents believe property values have been impacted by an environmental disamenity and, if so, “by how much.” Although there are important distinctions between the two techniques, with the contingent valuation method often preferred by economic practitioners, for simplicity no distinction is made here between these two approaches. Finally, another subset of the survey literature focuses on public acceptance (i.e., opinion). Though these public acceptance surveys sometimes cover possible impacts on property values, those impacts are not quantified in economic terms. As a result, public acceptance survey results are not reported here.

<sup>17</sup> Bond (2008) asked respondents to declare if the wind facility, which is located roughly 7 miles away, would effect what they would be willing to pay for their house and 75% said either they would pay the same or more for their house, while the remainder would pay less. When those latter respondents were asked to estimate the percentage difference in value, their estimates averaged roughly 5%.

construction have found no evidence of Area or Nuisance Stigmas (Grover, 2002; Goldman, 2006). These results, however, are contrary to the expectations for Area, Scenic Vista, and Nuisance Stigma effects predicted by local residents (Haughton et al., 2004; Firestone et al., 2007) and real estate experts (Haughton et al., 2004; Khatri, 2004; Kielisch, 2009) prior to construction found elsewhere.<sup>18</sup> The difference between predicted and actual effects might be attributable, at least in part, to the fear of the unknown. For instance, Wolsink (1989) found that public attitudes toward wind power, on average, are at their lowest for local residents during the wind project planning stage, but return almost to pre-announcement levels after the facilities are built. This result is echoed by Exeter-Enterprises-Ltd. (1993) and Palmer (1997), whose post-construction surveys found higher approval than those conducted pre-construction. Others, however, have found that perceptions do not always improve, attributing the lack of improvement to the perceived “success” or lack therefore of the project, with strong disapproval forming if turbines sit idle (Thayer and Freeman, 1987) or are perceived as a waste of taxpayer dollars (Devine-Wright, 2004).

When this literature is looked at as a whole, it appears as if wind projects have been predicted to negatively impact residential property values when pre-construction surveys are conducted, but that sizable, widespread, and statistically significant negative impacts have largely failed to materialize post-construction when actual transaction data become available for analysis. The studies that have investigated Area Stigma with market data have failed to uncover any pervasive effect. Of the studies focused on Scenic Vista and Nuisance Stigmas, only one is known to have found statistically significant adverse effects, yet the authors contend that those effects are likely driven by variables omitted from their analysis (Sims and Dent, 2007). Other studies that have relied on market data have sometimes found the possibility of negative effects, but the statistical significance of those results have rarely been reported.

Despite these findings, the existing literature leaves much to be desired. First, many studies have relied on surveys of homeowners or real estate professionals, rather than trying to quantify real price impacts based on market data. Second, a number of studies conducted rather simplified analyses of the underlying data, potentially not controlling for the many drivers of residential sales prices. Third, many of the studies have relied upon a very limited number of residential sales transactions, and therefore may not have had an adequate sample to statistically discern any property value effects, even if effects did exist. Fourth, and perhaps as a result, many of the studies did not conduct, or at least have not published, the statistical significance of their results. Fifth, when analyzed, there has been some emphasis on Area Stigma, and none of the studies have investigated all three possible stigmas simultaneously. Sixth, only a few of the studies (Hoen, 2006; Sims and Dent, 2007; Sims et al., 2008; Kielisch, 2009) conducted field visits to the homes to assess the quality of the scenic vista from the home, and the degree to which the wind facility might impact that scenic vista. Finally, with two exceptions (Sims and Dent, 2007; Sims et al., 2008), none of the studies have been academically peer-reviewed and published.

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<sup>18</sup> It should be noted that the samples used by both Khatri and Kielisch contained a subset of respondents who did have some familiarity with valuing homes near wind facilities.

**Table 1: Summary of Existing Literature on Impacts of Wind Projects on Property Values**

<u>Document Type</u> Author(s)	Year	Number of Transactions or Respondents	Before or After Wind Facility Construction Commenced	Area Stigma	Scenic Vista Stigma	Nuisance Stigma
<b><u>Homeowner Survey</u></b>						
Haughton et al.	2004	501	Before	- *	- *	
Goldman	2006	50	After	none		
Firestone et al.	2007	504	Before	- *	- *	
Bond	2008	~300	After		- ?	- ?
<b><u>Expert Survey</u></b>						
Grover	2002	13	After	none		none
Haughton et al.	2004	45	Before	- *	- *	
Khatri	2004	405	Before <sup>†</sup>	- ?		- ?
Goldman	2006	50	After	none		none
Kielisch	2009	57	Before <sup>‡</sup>			- ?
<b><u>Transaction Analysis - Simple Statistics</u></b>						
Jerabek	2001	25	After			none
Jerabek	2002	7	After			none
Sterzinger et al.	2003	24,000	After	none		
Beck	2004	2	After			none
Poletti	2005	187	After	none		none
DeLacy	2005	21	Before <sup>†</sup>	none		
Goldman	2006	4	After	none		
Poletti	2007	256	After	none		none
McCann	2008	2	After			- ?
Kielisch	2009	103	After			- ?
<b><u>Transaction Analysis - Hedonic Model</u></b>						
Jordal-Jorgensen	1996	?	After			- ?
Hoehn	2006	280	After		none	
Sims & Dent	2007	919	After			- *
Sims et al.	2008	199	After		-/+ *	
<i>" none " indicates the majority of the respondents do not believe properties have been affected (for surveys) or that no effect was detected at 10% significance level (for transaction analysis)</i>						
<i>" - ? " indicates a negative effect without statistical significance provided</i>						
<i>" - * " indicates statistically significant negative effect at 10% significance level</i>						
<i>" -/+ * " indicates positive and negative statistically significant effects at 10% significance level</i>						
<i>† Sales were collected after facility announcement but before construction</i>						
<i>‡ Some respondents had experience with valuations near facilities while others did not</i>						

### 3. Data Overview

The methods applied in the present work are intended to overcome many of the limitations of the existing literature. First, a large amount of data is collected from residential transactions within 10 miles of 24 different wind projects in the U.S., allowing for a robust statistical analysis across a pooled dataset that includes a diverse group of wind project sites. Second, all three potential stigmas are investigated by exploring the potential impact of wind projects on home values based both on the distance to and view of the projects from the homes. Third, field visits are made to every home in the sample, allowing for a solid assessment of the scenic vista enjoyed by each home and the degree to which the wind facility can be seen from the home, and to collect other value-influencing data from the field (e.g., if the home is situated on a cul-de-sac). Finally, a number of hedonic regression models are applied to the resulting dataset, as are repeat sales and sales volume analyses, in order to assess the robustness of the results.

Testing for the three potential stigmas requires a significant sample of residential transactions within close proximity to existing wind facilities. Unfortunately for the study, most wind power projects are not located near densely populated areas. As a result, finding a single wind project site with enough transaction data to rigorously analyze was not possible. Instead, the approach was to collect data from multiple wind project sites, with the resulting data then pooled together to allow for robust statistical analyses.<sup>19</sup> The remainder of this section describes the site selection process that is used, and provides a brief overview of both the selected study areas and the data that were collected from these areas. Also provided is a description of how scenic vista, views of turbines, and distances from turbines were quantified for use in the hedonic analysis, and a summary of the field data collection effort. The section ends with a brief summary of the resulting dataset.

#### 3.1. Site Selection

For the purpose of this study, an ideal wind project area would:

- 1) Have a large number of residential transactions both before and, more importantly, after wind facility construction, and especially in close proximity (e.g., within 2 miles) of the facility;
- 2) Have comprehensive data on home characteristics, sales prices, and locations that are readily available in electronic form; and
- 3) Be reasonably representative of the types of wind power projects being installed in the United States.

To identify appropriate sites that met these criteria, and that also provided a diversity of locations, the authors obtained from Energy Velocity, LLC a set of Geographic Information System (GIS) coordinates representing 241 wind projects in the U.S. that each had a total nameplate capacity greater than 0.6 megawatts (MW) and had gone online before 2006.<sup>20</sup> Also provided were facility capacity, number of turbines, and announcement, construction, and operational dates. These data were cross-checked with a similar dataset provided by the American Wind Energy Association (AWEA), which also included some turbine hub-height information.

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<sup>19</sup> A thorough discussion of this “pooled” approach is contained in Section 4.2 and in Appendix F.

<sup>20</sup> Energy Velocity, LLC was owned at the time by Global Energy Decisions, which was later purchased by Ventyx. The dataset is available as Velocity Suite 2008 from Ventyx.

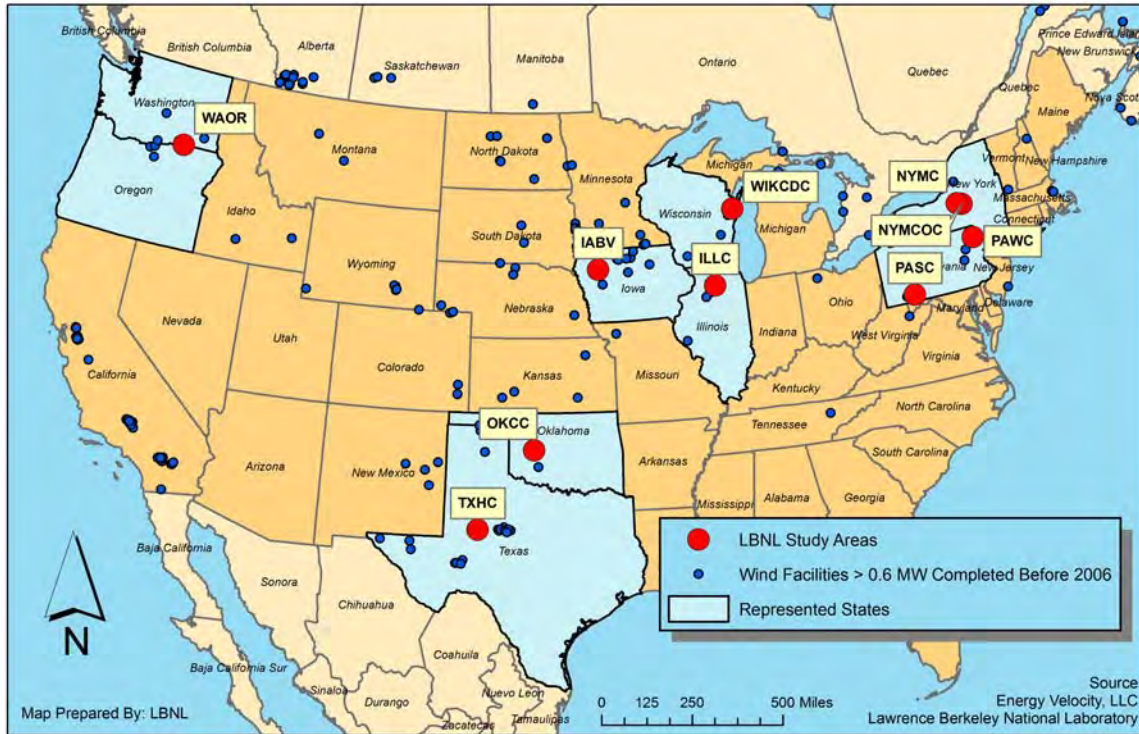
By using a variety of different GIS sorting techniques involving nearby towns with populations greater than, for example, 2,500 people, using census tract population densities, and having discussions with wind energy stakeholders, a prospective list of 56 possible study areas was generated, which were then ranked using two scales: “highly desirable” to “least desirable,” and “feasible” to “potentially unfeasible.”<sup>21</sup> Then, through an iterative process that combined calls to county officials to discuss the number of residential transactions and data availability, with investigations using mapping software to find the location of individual wind turbines, and, in some cases, preliminary visits, a list of 17 prospective study areas were chosen as both “highly desirable” and “feasible.” Ultimately, three of these proved to be “unfeasible” because of data availability issues and four “undesirable” because the study area was considered not representative. This effort ultimately resulted in a final set of ten study areas that encompass a total of 24 distinct wind facilities (see Figure 1 and Table 2).<sup>22</sup> A full description of each study area is provided in Appendix A.

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<sup>21</sup> “Desirability” was a combination of a number of factors: the wind facility having more than one turbine; the study area having greater than 350 sales within 5 miles and within 10 years, 250 of which transacted following construction of the facility; having some transaction data old enough to pre-date facility announcement; having data on the core home and site characteristics (e.g., square feet, acres); and, where possible, having a concentration of sales within 1 mile of the facility. “Feasibility” was also a combination of factors: having home characteristic and sales data in electronic form; having GIS shapefiles of the parcel locations; and being granted ready access to this information.

<sup>22</sup> The “unfeasible” study areas were Cerro Gordo County, IA, Bennington County, VT, and Atlantic County, NJ. Cerro Gordo County, IA contained multiple wind projects totaling 140 MW. Although the data at this site were available in electronic form, the county only agreed to share data in paper form, which would have created an enormous data entry burden. Because another site in the sample was considered similar to the Cerro Gordo site (IABV), Cerro Gordo County was dropped from the prospective sites. Bennington County, VT contained the 11 turbine Searsburg Wind Project (6 MW) but had no electronic records. Atlantic County, NJ contained the five turbine Jersey Atlantic Wind Farm (7.5 MW), but had data in paper records only and the county was unresponsive to inquiries regarding the study. The “undesirable” study areas were Plymouth County, MA, Wood County, OH, Cascade County, MT, and Riverside County, CA. Although the data in Plymouth County, MA were more than adequate, this small, on-land, yet coastal Hull Wind facility (2 turbines, 2.5 MW) was not considered to be particularly representative of wind development across the US. Wood County’s four turbine Bowling Green facility (7 MW) met the appropriate data requirements, but ultimately it was decided that this facility was too small and remote to be representative. Cascade County’s six turbine Horseshoe Bend Wind Park (9 MW) did not have enough transactions to justify study. Riverside, CA, where roughly 2500 turbines are located, had less-than-desired home characteristic data, had transactions that came more than 10 years after large scale development began, and despite having homes that were within 1 mile of the turbines, those homes typically had limited views because of high subdivision walls.

**Figure 1: Map of Study Areas and Potential Study Areas**



**Table 2: Summary of Study Areas**

Study Area Code	Study Area Counties, States	Facility Names	Number of Turbines	Number of MW	Max Hub Height (meters)	Max Hub Height (feet)
WAOR	Benton and Walla Walla Counties, WA and Umatilla County, OR	Vansycle Ridge, Stateline, Nine Canyon I & II, Combine Hills	582	429	60	197
TXHC	Howard County, TX	Big Spring I & II	46	34	80	262
OKCC	Custer County, OK	Weatherford I & II	98	147	80	262
IABV	Buena Vista County, IA	Storm Lake I & II, Waverly, Intrepid I & II	381	370	65	213
ILLC	Lee County, IL	Mendota Hills, GSG Wind	103	130	78	256
WIKCDC	Kewaunee and Door Counties, WI	Red River, Lincoln	31	20	65	213
PASC	Somerset County, PA	Green Mountain, Somerset, Meyersdale	34	49	80	262
PAWC	Wayne County, PA	Waymart	43	65	65	213
NYMCO	Madison and Oneida Counties, NY	Madison	7	12	67	220
NYMC	Madison County, NY	Fenner	20	30	66	218
		<b>TOTAL</b>	<b>1345</b>	<b>1286</b>		

These 10 study areas and 24 projects are located in nine separate states, and include projects in the Pacific Northwest, upper Midwest, the Northeast, and the South Central region. The wind projects included in the sample total 1,286 MW, or roughly 13% of total U.S. wind power capacity installed at the time (the end of 2005). Turbine hub heights in the sample range from a

minimum of 164 feet (50 meters) in the Washington/Oregon (WAOR) study area, to a maximum of 262 (80 meters) (TXHC, OKCC and PASC), with nine of the ten study areas having hub heights of at least 213 feet (65 meters). The sites include a diverse variety of land types, including combinations of ridgeline (WAOR, PASC, and PAWC), rolling hills (ILLC, WIKCDC, NYMCOC, and NYMC), mesa (TXHC), and windswept plains (OKCC, IABV).<sup>23</sup>

## 3.2. Data Collection

In general, for each study area, residential transaction data in as close proximity to the wind turbines as possible was sought, from both before and after wind facility construction. To balance the cost and quantity of data collection in each study area with the desire to cover as many study areas as possible, the research effort sought to collect data on 400 to 1,250 transactions in each study area.<sup>24</sup> In some instances, this meant including all residential transactions within ten miles of the wind turbines. In others, only transactions within five miles were included. In some extreme instances, when the number of transactions inside of five miles far exceeded the 1,250 limit, all transactions in close proximity to the wind turbines (e.g., inside three miles) were included in combination with a random sample of transactions outside of that distance band (e.g., between three and five miles).<sup>25</sup> The data selection processes for each Study Area are contained in Appendix A.

Three primary sets of data are used in the analysis: tabular data, GIS data, and field data, each of which is discussed below. Following that, this subsection highlights the two qualitative variables that are essential to this analysis and that therefore require special attention, scenic vista and views of turbines, and then discusses the field data collection process.

### 3.2.1. Tabular Data

Berkeley Lab obtained tabular transaction data from participating counties<sup>26</sup> containing 7,459 “valid”<sup>27</sup> transactions of single family residential homes, on less than 25 acres,<sup>28</sup> which were

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<sup>23</sup> Some areas, such as PASC, had both a ridgeline and rolling hills on which wind facilities were located.

<sup>24</sup> This range was chosen to ensure that a minimum of data were present in each study area to allow for a robust analysis, and yet not too much so as to make data collection (e.g., the visiting of each home) inordinately time and resource consuming in any individual study area.

<sup>25</sup> An alternative method would have been to collect data on every sale that occurred. Although in most cases this would be preferred, in ours it would not have added one additional transaction within close proximity or with dramatic views of wind turbine, the focus of the study. Rather, it would have added an overwhelming majority of transactions of homes without views and at distances outside of three miles from the turbines, all of which would have come at considerably cost and, more importantly, would not likely have influenced the results significantly while perhaps necessitating a reduction in the total number of study areas that could be included in the sample.

<sup>26</sup> In some cases, the county officials, themselves, extracted data from their database, and in some cases a company engaged to manage a county’s data provided the necessary information. In either case the provider is referred to as “county.” Detailed descriptions of the providers are presented in Appendix A.

<sup>27</sup> Validity was determined by each individual county data provider. A sale that is considered “valid” for county purposes would normally meet the minimum requirements of being arm’s length; being a transfer of all rights and warrants associated with the real estate; containing an insignificant amount of personal property so as not to affect the price; demonstrating that neither party in the sale acting under duress or coercion; not being the result of a liquidation of assets or any other auction, a mortgage foreclosure, a tax sale, or a quit claim; and being appropriate for use in calculating the sales price to assessed value ratios that are reported to the state. Due to the formal requirements associated with this calculation, “validity” is often defined by a state’s Department of Revenue, as shown, for example, here: <http://www.orps.state.ny.us/assessor/manuals/vol6/rfv/index.htm>. In addition, though the



sold for a price of more than \$10,000,<sup>29</sup> which occurred after January 1, 1996,<sup>30</sup> and which had fully populated “core” home characteristics. These core characteristics are: number of square feet of the living area (not including finished basement), acres of land, bathrooms, and fireplaces, the year the home was built,<sup>31</sup> if the home had exterior wall that were stone, a central air conditioning unit, and/or a finished basement, and the exterior condition of the home. The 7,459 residential transactions in the sample consist of 6,194 homes (a number of the homes in the sample sold more than once in the selected study period). Because each transaction had a corresponding set of the core home characteristic data, they could all be pooled into a single model. In addition to the home characteristic data, each county provided, at a minimum, the home’s physical address and sales price. The counties often also provided data on homes in the study area that did not sell in the study period.<sup>32</sup> Finally, market-specific quarterly housing inflation indexes were obtained from Freddie Mac, which allowed nominal sales prices to be adjusted to 1996 dollars.<sup>33</sup>

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sample originally contained 7,498 sales, 34 homes sold twice in a 6 month period and, after discussions with local officials, these transactions were considered likely to have been “invalid” despite the county coding them to the contrary. Additionally, five transactions produced standardized residuals that were more than six standard deviations away from the mean, indicating that these sales were abnormal and likely not valid. Both of these sets of transactions, totaling 39, were removed from the final dataset. Of the 39 sales, 32 sold following construction, 10 were concentrated in IABV and nine in TXHC with the others spread between seven of the remaining eight study areas. One of the homes was inside of one mile from the turbines at the time of sale, and two had views of the turbines (both of which were MINOR). The home that was located within one mile was surrounded by a number of other homes – at similar distances from the turbines - that transacted both before and after the wind facilities were built and were included in the sample. A more thorough discussion of the screening techniques used to ensure the appropriateness of the final data set are presented in detail in Appendix G under “Outliers/Influencers.” Finally, it should be noted that the authors are aware of four instances in the study areas when homes were sold to wind developers. In two cases the developer did not resell the home; in the other two, the developer resold the home at a lower price than which it was purchased. But, because the sales were to a related party, these transactions were not considered “valid” and are therefore not included here. One might, however, reasonably expect that the property values of these homes were impacted by the presence of the wind turbines.

<sup>28</sup> Single family residences on more than 25 acres were considered to be likely candidates for alternative uses, such as agricultural and recreational, which could have an influence on sales price that was outside of the capabilities of the model to estimate. Because all records were for parcels that contained a residence, the model did not contain any “land-only” transactions. Further, none of the transactions provided for this research were for parcels on which a turbine was located.

<sup>29</sup> A sales price of \$10,000 was considered the absolute minimum amount an improved parcel (one containing a residential structure) would sell for in any of the study areas and study periods. This provided an additional screen over and above the “valid” screen that the counties performed.

<sup>30</sup> This provided a maximum of 12 years of data. Some counties did not have accessible data back to 1996 but in all cases these countries had data on transactions that occurred before the wind facilities were erected.

<sup>31</sup> “Year Built” was used to construct a variable for the age of the home at the time of the sale.

<sup>32</sup> These data were used to calculate the “Sales Volume” percentages referred to in Section 7.

<sup>33</sup> Freddie Mac Conventional Mortgage Home Price Index: municipal statistical area (MSA) series data are available from the following site: <http://www.freddiemac.com/finance/cmhpi/>. Because most of the study areas do not fall within the MSAs, a collection of local experts was relied upon, including real estate agents, assessors, and appraisers, to decide which MSA most-closely matched that of the local market. In all cases the experts had consensus as to the best MSA to use. In one case (NYMCOC) the sample was split between two MSAs. These indexes are adjusted quarterly, and span the entire sample period. Therefore, during the housing boom, insofar as a boom occurred in the sample areas, the indexes increased in value. Subsequently when the market began falling, the index retracted.

### 3.2.2. GIS Data

GIS data on parcel location and shape were also required, and were obtained from the counties. The counties also often provided GIS layers for roads, water courses, water bodies, wind turbines (in some cases), house locations, and school district and township/town/village delineations. GIS data on census tract and school district delineations were obtained from the U.S. Census Bureau, if not provided by the county.<sup>34</sup> GIS data were obtained on water courses, water bodies, land elevations, and satellite imagery, as was necessary, from the U.S. Department of Agriculture.<sup>35</sup> Combined, these data allowed each home to be identified in the field, the construction of a GIS layer of wind turbine locations for each facility, and the calculation of the distance from each home to the nearest wind turbine.<sup>36</sup> Determining the distance from each home to the nearest wind turbine was a somewhat involved process, and is discussed in detail in Appendix B. Suffice it to say that each transaction had a unique distance (“DISTANCE”)<sup>37</sup> that was determined as the distance between the home and nearest wind turbine at the time of sale, and that these distances are grouped into five categories: inside of 3000 feet (0.57 miles), between 3000 feet and one mile, between one and three miles, between three and five miles, and outside of five miles.<sup>38</sup> Finally, the GIS data were used to discern if the home was situated on a cul-de-sac and had water frontage, both of which were corroborated in the field.

### 3.2.3. Field Data

Additional data had to be collected through field visits to all homes in the sample. Two qualitative measures in particular – for scenic vista and for view of the wind turbines – are worth discussing in detail because each is essential to the analysis and each required some amount of professional judgment in its creation.

The impact or severity of the view of wind turbines (“VIEW”)<sup>39</sup> may be related to some combination of the number of turbines that are visible, the amount of each turbine that is visible (e.g., just the tips of the blades or all of the blades and the tower), the distance to the nearest turbines, the direction that the turbines are arrayed in relation to the viewer (e.g., parallel or perpendicular), the contrast of the turbines to their background, and the degree to which the turbine arrays are harmoniously placed into the landscape (Gipe, 2002). Recent efforts have made some progress in developing quantitative measures of the aesthetic impacts of wind turbines (Torres-Sibillea et al., 2009),<sup>40</sup> but, at the time this project began, few measures had

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<sup>34</sup> These data were sourced from the U.S. Census Bureau’s Cartographic Boundary Files Webpage: [http://www.census.gov/geo/www/cob/bdy\\_files.html](http://www.census.gov/geo/www/cob/bdy_files.html).

<sup>35</sup> These data were sourced from the USDA Geospatial Data Gateway: <http://datagateway.nrcs.usda.gov/GatewayHome.html>.

<sup>36</sup> Although in some cases the county provided a GIS layer containing wind turbine points, often this was not available. A description of the turbine mapping process is provided in Appendix B.

<sup>37</sup> Distance measures are collectively and individually referred to as “DISTANCE” from this point forward.

<sup>38</sup> The minimum distance of “inside 3000 feet” was chosen because it was the closest cutoff that still provided an ample supply of data for analysis.

<sup>39</sup> View of turbines ratings are collectively and individually referred to as “VIEW” from this point forward.

<sup>40</sup> In addition to these possible field techniques, previous studies have attempted to use GIS to estimate wind turbine visibility using “line-of-sight” algorithms. For example, Hoen (2006) used these algorithms after adding ground cover to the underlying elevation layer. He found that the GIS method differed substantially from the data collected in the field. Seemingly, small inaccuracies in the underlying elevation model, errors in the software’s algorithm, and the existence of ground cover not fully accounted for in the GIS, substantially biased GIS-based assessments of

been developed, and what had been developed was difficult to apply in the field (e.g., Bishop, 2002). As a result, the authors opted to develop an ordered qualitative VIEW rating system that consisted of placing the view of turbines into one of five possible categories: NO VIEW, MINOR, MODERATE, SUBSTANTIAL, and EXTREME. These ratings were developed to encompass considerations of distance, number of turbines visible, and viewing angle into one ordered categorical scale, and each rating is defined in Table 3:<sup>41</sup>

**Table 3: Definition of VIEW Categories**

NO VIEW	The turbines are not visible at all from this home.
MINOR VIEW	The turbines are visible, but the scope (viewing angle) is narrow, there are many obstructions, or the distance between the home and the facility is large.
MODERATE VIEW	The turbines are visible, but the scope is either narrow or medium, there might be some obstructions, and the distance between the home and the facility is most likely a few miles.
SUBSTANTIAL VIEW	The turbines are dramatically visible from the home. The turbines are likely visible in a wide scope and most likely the distance between the home and the facility is short.
EXTREME VIEW	This rating is reserved for sites that are unmistakably dominated by the presence of the wind facility. The turbines are dramatically visible from the home and there is a looming quality to their placement. The turbines are often visible in a wide scope or the distance to the facility is very small.

*Photographic examples of each of the categories are contained in Appendix E.*

visibility. This was corroborated elsewhere by Maloy and Dean (2001) and Riggs and Dean (2007). As a result of these findings, it was determined that field collection of VIEW data was essential.

<sup>41</sup>In addition to the qualitative rating system that was ultimately used in this study, a variety of quantitative data were collected that might describe the nature of the view of wind turbines, including the total number of turbines visible, the distance of the home to the nearest wind turbine, and the view scope/viewing angle (i.e., the degree to which the turbines spread out in front of the home: narrow, medium, or wide). To explore the validity of the qualitative rating scale two tests were conducted. First, a pre-study survey was conducted by showing 10 different off-site respondents 15 randomly selected photographs from the field representing the various rated VIEW categories. The higher VIEW ratings were oversampled to create a roughly equal distribution among the categories. The respondents rated the views into one of the qualitative categories. The on-site / field collected ratings matched the off-site responses 65% of the time, with 97% of the rankings differing by no more than one category. Ninety-eight percent of the on-site-ranked MINOR VIEWS and 89% of the EXTREME VIEWS were similarly ranked by off-site respondents. The on-site rankings were less than the off-site rankings 97% of the time; it is assumed that this is because on-site ratings took into account a greater portion of the panorama than were captured in the photos, which translated into a lower ranking. Secondly, a post hoc Multinomial Logistic Regression model was created that used the qualitative on-site VIEW ratings as the dependent variable and the quantitative measures of distance to nearest turbine, number of turbines visible, and view scope as the independent variables. This model produced high Pseudo R<sup>2</sup> statistics (Cox and Snell 0.88, Nagelkerke 0.95, and McFadden 0.79) and predicted values that were highly correlated with the actual qualitative rating (Pearson's 0.88). Therefore, both tests corroborated the appropriateness of the simpler qualitative VIEW rankings used herein.

In addition to the qualitative VIEW measurements, a rating for the quality of the scenic vista (“VISTA”)<sup>42</sup> from each home, absent the existence of the wind facilities, was also collected in the field. An assessment of the quality of the VISTA from each home was needed because VIEW and VISTA are expected to be correlated; for example, homes with a PREMIUM VISTA are more likely to have a wide viewing angle in which wind turbines might also be seen. Therefore, to accurately measure the impacts of the VIEW of wind turbines on property values a concurrent control for VISTA (independent of any views of turbines) is required. Drawing heavily on the landscape-quality rating system developed by Buhyoff et al. (1994) and to a lesser degree on the systems described by others (Daniel and Boster, 1976; USDA, 1995), an ordered VISTA rating system consisting of five categories was developed: POOR, BELOW AVERAGE, AVERAGE, ABOVE AVERAGE, and PREMIUM, with each rating defined in Table 4:<sup>43</sup>

**Table 4: Definition of VISTA Categories**

POOR VISTA	These vistas are often dominated by visually discordant man-made alterations (not considering turbines), or are uncomfortable spaces for people, lack interest, or have virtually no recreational potential.
BELOW AVERAGE VISTA	These scenic vistas contain visually discordant man-made alterations (not considering turbines) but are not dominated by them. They are not inviting spaces for people, but are not uncomfortable. They have little interest or mystery and have minor recreational potential.
AVERAGE VISTA	These scenic vistas include interesting views that can be enjoyed often only in a narrow scope. These vistas may contain some visually discordant man-made alterations (not considering turbines), are moderately comfortable spaces for people, have some interest, and have minor recreational potential.
ABOVE AVERAGE VISTA	These scenic vistas include interesting views that often can be enjoyed in a medium to wide scope. They might contain some man-made alterations (not considering turbines), yet still possess significant interest and mystery, are moderately balanced and have some potential for recreation.
PREMIUM VISTA	These scenic vistas would include "picture postcard" views that can be enjoyed in a wide scope. They are often free or largely free of any discordant man made alterations (not considering turbines), possess significant interest, memorable qualities, and mystery and are well balanced and likely have a high potential for recreation.

*Photographic examples of each of the categories are contained in Appendix D.*

<sup>42</sup> Scenic vista ratings are individually and collectively referred to as “VISTA” from this point forward.

<sup>43</sup> The appropriateness of these rankings were tested in two ways. First, a set of 34 pictures taken on-site and representing various categories of VISTA were shown to 10 off-site respondents who were asked to rank them using the same categories, and then explain why they rated them as such. Although the off-site ratings matched the on-site ratings only 51% of the time, 94% of on- and off-site rankings differed by no more than one category, with 17% of the off-site rankings below the on-site and 26% ranked above. The descriptions of why the rankings were chosen by the off-site respondents illuminated the fact that off-site ratings did not take into account a number of aspects that were not adequately captured in the photos, but that were apparent in the field. This finding was borne out by a second test that had five individuals visit seven homes in the field to rank their scenic vistas. When all respondents were on-site, they similarly ranked the vista 72% of the time, with a ranking that differed by no more than one category occurring one hundred percent of the time.

In addition to the VIEW and VISTA ratings, it was assumed that the orientation of the home to the view of turbines (e.g., front, back, or side) (“ORIENTATION”), and the degree to which the view of the turbines overlapped the primary scenic vista (e.g., not at all, barely, somewhat or strongly) (“OVERLAP”), might influence residential property values. As such, information on ORIENTATION and OVERLAP were also collected in the field.

### 3.2.4. Field Data Collection

Field data collection was conducted on a house-by-house basis. Each of the 6,194 homes was visited by the same individual to remove bias among field ratings. Data collection was conducted in the fall of 2006, and the spring, summer, and fall of 2007 and 2008. Each house was photographed and, when appropriate, so too were views of turbines and the prominent scenic vista.<sup>44</sup> Data on VIEW were collected only for those homes that sold after at least one wind power facility had been erected in the study area. When multiple wind facilities, with different construction dates, were visible from a home, field ratings for VIEW were made by taking into account which turbines had been erected at the time of sale. Additionally, if the season at the time of sale differed from that of data collection and, for example, if leaves were off the trees for one but on for the other, an effort was made to modulate the VIEW rating accordingly if necessary.<sup>45</sup>

Both VIEW and VISTA field ratings were arrived at through a Q-Sort method (Pitt and Zube, 1979), which is used to distinguish relatively similar rankings. For views of turbines, the rater first determined if the ranking was MINOR or EXTREME. If neither of these two rankings was appropriate, then only a choice between MODERATE and SUBSTANTIAL was required. Similarly, for VISTA rankings, first POOR and PREMIUM were distinguished from the others; if neither applied then BELOW AVERAGE or ABOVE AVERAGE could be selected. If neither of those were appropriate the VISTA, by default, was considered AVERAGE. In all cases, if wind turbines were visible from the home, the VISTA rankings were made as if those turbines did not exist.

### 3.3. Data Summary

The final dataset consists of 7,459 valid and screened residential transactions occurring between January 2, 1996 and June 30, 2007. Those transactions are arrayed across time and the ten wind project study areas as shown in Table 5. The sample of valid residential transactions ranges from 412 in Lee County, Illinois (ILLC) to 1,311 in Howard County, Texas (TXHC).<sup>46</sup> Of the total 7,459 transactions, 4,937 occurred after construction commenced on the relevant wind facilities. More specifically, 23% of the transactions ( $n=1,755$ ) took place before any wind facility was announced and 10% occurred after announcement but before construction commenced ( $n=767$ ),

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<sup>44</sup> In many cases the prominent VISTA was homogenous across groups of home, for instance urban homes on the same road. In those cases a picture of the VISTA of one home was applied to all of the homes. All pictures were taken with a Canon EOS Rebel XTi Single Lens Reflex Camera with a 18-55mm lens. VIEW and VISTA pictures were taken with the lens set to 18mm, with the camera at head height, and with the center of the camera pointed at the center of the prominent VISTA or VIEW. Examples of the various VISTA and VIEW categories are contained in Appendices D and E respectively.

<sup>45</sup> This “modulation” occurred only for trees in the foreground, where, for instance, a single tree could obscure the view of turbines; this would not be the case for trees nearer the horizon.

<sup>46</sup> See description of “valid” in footnote 27 on page 13.

with the rest of the transactions occurring after construction commenced (66%,  $n=4,937$ ).<sup>47</sup> Of that latter group, 17% ( $n=824$ , 11% of total) sold in the first year following the commencement of construction, 16% in the second year ( $n=811$ , 11% of total), and the remainder (67%) sold more than two years after construction commenced ( $n=3,302$ , 44% of total).

**Table 5: Summary of Transactions across Study Areas and Development Periods**

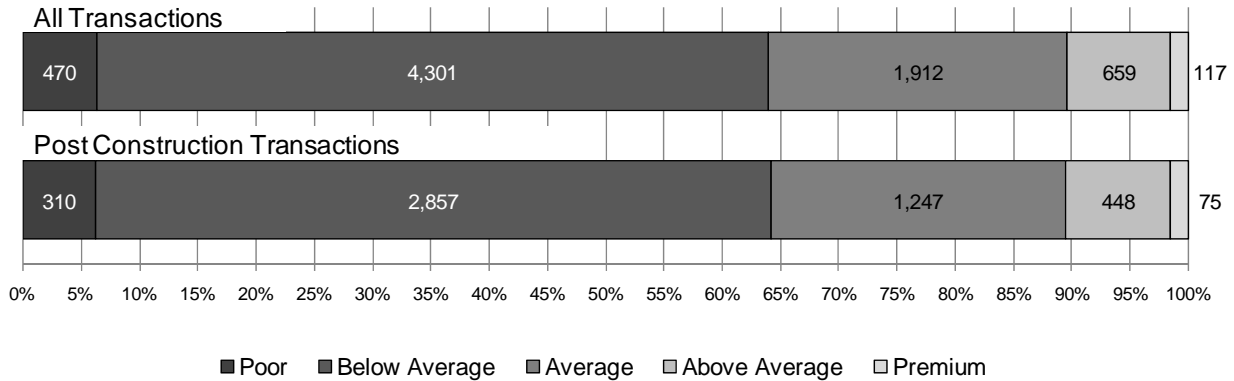
	Pre Announcement	Post Announcement Pre Construction	1st Year After Construction	2nd Year After Construction	2+ Years After Construction	Total
<b>Benton/Walla Walla, WA &amp; Umatilla, OR (WAOR)</b>	226	45	76	59	384	<b>790</b>
<b>Howard, TX (TXHC)</b>	169	71	113	131	827	<b>1311</b>
<b>Custer, OK (OKCC)</b>	484	153	193	187	96	<b>1113</b>
<b>Buena Vista, IA (IABV)</b>	152	65	80	70	455	<b>822</b>
<b>Lee, IL (ILLC)</b>	115	84	62	71	80	<b>412</b>
<b>Kewaunee/Door, WI (WIKCDC)</b>	44	41	68	62	595	<b>810</b>
<b>Somerset, PA (PASC)</b>	175	28	46	60	185	<b>494</b>
<b>Wayne, PA (PAWC)</b>	223	106	64	71	87	<b>551</b>
<b>Madison/Oneida, NY (MYMCOC)</b>	108	9	48	30	268	<b>463</b>
<b>Madison, NY (NYMC)</b>	59	165	74	70	325	<b>693</b>
<b>TOTAL</b>	<b>1755</b>	<b>767</b>	<b>824</b>	<b>811</b>	<b>3302</b>	<b>7459</b>

A basic summary of the resulting dataset, including the many independent variables used in the hedonic models described later, is contained in Table 6 and Table 7. These tables present summary information for the full dataset (7,459 transactions) as well as the post-construction subset of that dataset (4,937 transactions); the latter is provided because much of the analysis that follows focuses on those homes that sold after wind facility construction. The mean nominal residential transaction price in the sample is \$102,968, or \$79,114 in 1996 dollars. The average house in the sample can be described as follows: it is 46 years old, has 1,620 square feet of finished living area above ground, is situated on 1.13 acres, has 1.74 bathrooms, and has a

<sup>47</sup> The announcement date (as well as construction and online dates) was provided by Energy Velocity with the GIS files as described in footnote 20 on page 10. The date corresponds to the first time the facility appears in the public record, which was often the permit application date. This constitutes the first well established date when the existing wind facility would have been likely known by the public, and therefore is appropriate to use for this analysis, but there remain a number of areas for potential bias in this date. First, the permit application date might be preceded by news reports of the impending application; alternatively, if the public record was not published online (that Energy Velocity used to establish their date), the “announcement” date – as used here - could, in fact, follow the permit application date. To address this, when possible, the authors had discussions with the developer of the facility. In most cases, the Energy Velocity dates were found to be accurate, and when they were not they were adjusted to reflect the dates provided by the developer. A second potential source of bias is the possibility that a different project was proposed but never built, but that influenced the residential market in the study area prior to the “announcement” date. Although this is likely rarer, we are aware of at least a few projects that fit that description in the study areas. A final source of bias might revolve around the likelihood that awareness of a project could occur even before the facility is formally announced. For example, a community member might know that a wind facility is being considered because they had been approached by the wind development company well ahead of a public announcement. In turn, they might have had private discussions regarding the facility with other members of the community. Taken together, it is appropriate to assume that there is some bias in the “announcement” date, and that awareness of the project might precede the date used in this analysis. How this bias might affect the results in this report is addressed further in Section 5.3 and footnote 74 on page 38.

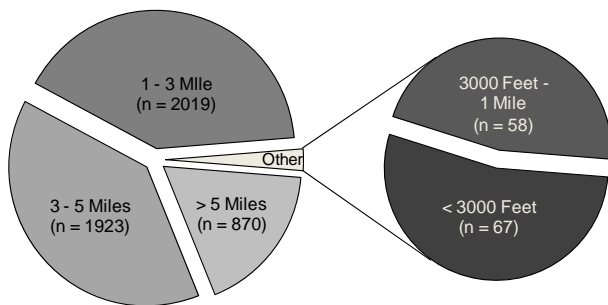
slightly better than average condition.<sup>48</sup> Within the full sample, 6% and 58% of homes had a poor or below average VISTA rating, respectively; 26% of homes received an average rating on this scale, with 9% above average and 2% experiencing premium vistas (see Figure 2).

**Figure 2: Frequency of VISTA Ratings for All and Post-Construction Transactions**



With respect to the variables of interest, among the post-construction subset of 4,937 transactions, the frequency of the DISTANCE categories is found to follow geometry with the smallest numbers of transactions occurring near the wind turbines and ever increasing numbers further away (see Figure 3). 67 transactions (1%) are situated inside of 3,000 feet (< 0.57 Miles), 58 (1%) are between 3,000 feet and one mile (0.57-1 mile), 2,019 (41%) occur outside of one mile but inside of three miles (1-3 miles), 1,923 (39%) occur between three and five miles (3-5 miles), and 870 (18%) occur outside of five miles (>5 miles).<sup>49</sup> In this same post-construction group, a total of 730 homes that sold (15%) have a view of the wind turbines (see Figure 4). A large majority of those homes have MINOR view ratings ( $n = 561$ , 11% of total), with 2% having MODERATE ratings ( $n=106$ ) and the remaining transactions roughly split between SUBSTANTIAL and EXTREME ratings ( $n=35$ , 0.6%, and  $n=28$ , 0.5%, respectively). A full description of the variables of interest and how they are arrayed at the study area level is contained in Appendix A.

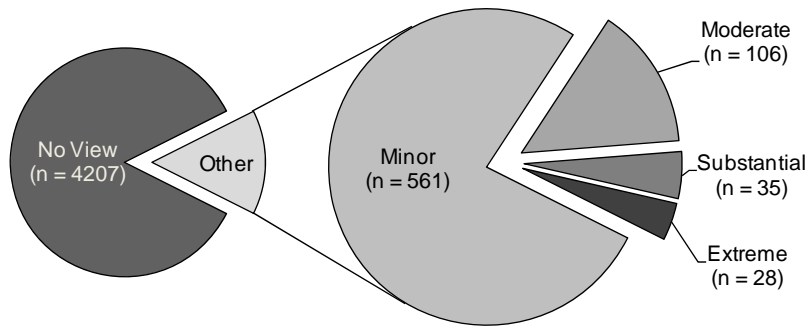
**Figure 3: Frequency of DISTANCE Ratings for Post-Construction Transactions**



<sup>48</sup> The variable for the condition of the home was not uniform across study areas because, in some cases, it took into account construction grade while in others it did not.

<sup>49</sup> These numbers and percentages are skewed slightly from the overall population of transactions because homes outside of three miles were often under-sampled to reduce field data collection burdens. Further, higher numbers of homes fall into each of the categories when the post-announcement-pre-construction transactions are included, as they are in some models. These additional transactions are described below in Table 7 under “All Sales.”

**Figure 4: Frequency of VIEW Ratings for Post-Construction Transactions**



**Table 6: Summary Statistics: All Sales and Post-Construction Sales**

Variable Name	Description	All Sales			Post Construction Sales		
		Freq. *	Mean	Std. Dev.	Freq. *	Mean	Std. Dev.
SalePrice	The unadjusted sale price of the home (in US dollars)	7,459	102,968	64,293	4,937	110,166	69,422
SalePrice96	The sale price of the home adjusted to 1996 US dollars	7,459	79,114	47,257	4,937	80,156	48,906
LN_SalePrice96	The natural log transformation of the sale price of the home adjusted to 1996 US dollars	7,459	11.12	0.58	4,937	11.12	0.60
AgeatSale	The age of the home at the time of sale	7,459	46	37	4,937	47	36
AgeatSale_Sqrd	The age of the home at the time of sale squared	7,459	3,491	5,410	4,937	3,506	5,412
Sqft_1000	The number of square feet of above grade finished living area (in 1000s)	7,459	1.623	0.59	4,937	1.628	0.589
Acres	The number of Acres sold with the residence	7,459	1.13	2.42	4,937	1.10	2.40
Baths	The number of Bathrooms (Full Bath = 1, Half Bath = 0.5)	7,459	1.74	0.69	4,937	1.75	0.70
ExtWalls_Stone	If the home has exterior walls of stone, brick or stucco (Yes = 1, No = 0)	2,287	0.31	0.46	1,486	0.30	0.46
CentralAC	If the home has a Central AC unit (Yes = 1, No = 0)	3,785	0.51	0.50	2,575	0.52	0.50
Fireplace	The number of fireplace openings	2,708	0.39	0.55	1,834	0.40	0.55
Cul_De_Sac	If the home is situated on a cul-de-sac (Yes = 1, No = 0)	990	0.13	0.34	673	0.14	0.34
FinBsmt	If finished basement square feet is greater than 50% times first floor square feet (Yes = 1, No = 0)	1,472	0.20	0.40	992	0.20	0.40
Water_Front	If the home shares a property line with a body of water or river (Yes = 1, No = 0)	107	0.01	0.12	87	0.02	0.13
Cnd_Low	If the condition of the home is Poor (Yes = 1, No = 0)	101	0.01	0.12	69	0.01	0.12
Cnd_BAvg	If the condition of the home is Below Average (Yes = 1, No = 0)	519	0.07	0.25	359	0.07	0.26
Cnd_Avg	If the condition of the home is Average (Yes = 1, No = 0)	4,357	0.58	0.49	2,727	0.55	0.50
Cnd_AAVg	If the condition of the home is Above Average (Yes = 1, No = 0)	2,042	0.27	0.45	1,445	0.29	0.46
Cnd_High	If the condition of the home is High (Yes = 1, No = 0)	440	0.06	0.24	337	0.07	0.25
Vista_Poor	If the Scenic Vista from the home is Poor (Yes = 1, No = 0)	470	0.06	0.24	310	0.06	0.24
Vista_BAvg	If the Scenic Vista from the home is Below Average (Yes = 1, No = 0)	4,301	0.58	0.49	2,857	0.58	0.49
Vista_Avg	If the Scenic Vista from the home is Average (Yes = 1, No = 0)	1,912	0.26	0.44	1,247	0.25	0.44
Vista_AAVg	If the Scenic Vista from the home is Above Average (Yes = 1, No = 0)	659	0.09	0.28	448	0.09	0.29
Vista_Prem	If the Scenic Vista from the home is Premium (Yes = 1, No = 0)	117	0.02	0.12	75	0.02	0.12
SaleYear	The year the home was sold	7,459	2002	2.9	4,937	2004	2.3

\* "Freq." applies to the number of cases the parameter's value is not zero



**Table 7: Summary of Variables of Interest: All Sales and Post-Construction Sales**

Variable Name	Description	All Sales			Post Construction Sales		
		Freq. *	Mean	Std. Dev.	Freq. *	Mean	Std. Dev.
<b>View_None</b>	If the home sold after construction began and had no view of the turbines (Yes = 1, No = 0)	4,207	0.56	0.50	4,207	0.85	0.36
<b>View_Minor</b>	If the home sold after construction began and had a Minor View of the turbines (Yes = 1, No = 0)	561	0.08	0.26	561	0.11	0.32
<b>View_Mod</b>	If the home sold after construction began and had a Moderate View of the turbines (Yes = 1, No = 0)	106	0.01	0.12	106	0.02	0.15
<b>View_Sub</b>	If the home sold after construction began and had a Substantial View of the turbines (Yes = 1, No = 0)	35	-	0.07	35	0.01	0.08
<b>View_Extrm</b>	If the home sold after construction began and had an Extreme View of the turbines (Yes = 1, No = 0)	28	-	0.06	28	0.01	0.08
<b>DISTANCE †</b>	Distance to nearest turbine if the home sold after facility "announcement", otherwise 0	5,705	2.53	2.59	4,895	3.57	1.68
<b>Mile_Less_0.57 †</b>	If the home sold after facility "announcement" and was within 0.57 miles (3000 feet) of the turbines (Yes = 1, No = 0)	80	0.01	0.09	67	0.01	0.12
<b>Mile_0.57to1 †</b>	If the home sold after facility "announcement" and was between 0.57 miles (3000 feet) and 1 mile of the turbines (Yes = 1, No = 0)	65	0.01	0.09	58	0.01	0.11
<b>Mile_1to3 †</b>	If the home sold after facility "announcement" and was between 1 and 3 miles of the turbines (Yes = 1, No = 0)	2,359	0.27	0.44	2,019	0.41	0.49
<b>Mile_3to5 †</b>	If the home sold after facility "announcement" and was between 3 and 5 miles of the turbines (Yes = 1, No = 0)	2,200	0.26	0.44	1,923	0.39	0.49
<b>Mile_Gtr5 †</b>	If the home sold after facility "announcement" and was outside 5 miles of the turbines (Yes = 1, No = 0)	1,000	0.12	0.32	870	0.18	0.38

\* "Freq." applies to the number of cases the parameter's value is not zero

† "All Sales" freq., mean and standard deviation DISTANCE and DISTANCE fixed effects variables (e.g., Mile\_1to3) include transactions that occurred after facility "announcement" and before "construction" as well as those that occurred post-construction

## 4. Base Hedonic Model

This section uses the primary hedonic model (“Base Model”) to assess whether residential sales prices are affected, in a statistically measurable way, by views of and proximity to wind power facilities. In so doing, it simultaneously tests for the presence of the three potential property value stigmas associated with wind power facilities: Area, Scenic Vista, and Nuisance. This section begins with a discussion of the dataset that is used and the form of the model that is estimated, and then turns to the results of the analysis. Various alternative hedonic models are discussed and estimated in Section 5, with Sections 6 and 7 providing a discussion of and results from the repeat sales and sales volume models.

### 4.1. Dataset

The data used for the Base Model were described in Section 3.3. A key threshold question is whether or not to include the residential transactions that pre-date the relevant wind facility. Specifically, though the complete dataset consists of 7,459 residential transactions, a number of these transactions ( $n = 2,522$ ) occurred before the wind facility was constructed. Should these homes which, at the time of sale, would not have had any view of or distance to the wind facility, be included? Two approaches could be applied to address this issue. First, pre-construction transactions could be included in the hedonic model either as part of the reference category within which no wind-project property value impacts are assumed to exist, or instead by specifically identifying these pre-construction transactions through an indicator variable. Second, and alternatively, pre-construction transactions could simply be excluded from the analysis altogether.

For the purpose of the Base Model, the latter approach is used, therefore relying on only the post-construction subset of 4,937 residential transactions. This approach, as compared to the others, results in somewhat more intuitive findings because all homes have a distance greater than zero and have a possibility of some view of the turbines. More importantly, this approach minimizes the chance of inaccuracies that may otherwise exist due to inflation adjustment concerns or outdated home characteristics information.<sup>50</sup> Nonetheless, to test for the implications of this choice of datasets, alternative hedonic models that use the full dataset were estimated, and are discussed in detail in Sections 5.3 and 5.4.

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<sup>50</sup> Home characteristics were obtained as of the last property assessment. The timing of that assessment relative to the timing of the home sale transaction dictates how representative the assessed home characteristics are of the subject home when it was sold. For example, if a home sold early in the study period but subsequently had significant improvements made that are reflected in the current assessment data used in the analysis, the model would assign value to these home characteristics at the time of sale when, in fact, those characteristics were inaccurate. Additionally, the inflation adjustment index used in this analysis to translate home values to real 1996 dollars came from the nearest or more appropriate municipal statistical area (MSA). Many of the wind projects in the analysis are located in relatively rural parts of the country, and the housing market in the nearest metropolitan area could be different than the market surrounding wind projects. Although these areas have – in many instances – recently begun to attract home buyers willing to commute back to the metropolitan areas on which the index is based, the older index adjustments are likely less accurate than the more recent adjustments. Using a subset of the data for the majority of the analyses that removes the older, pre-construction, homes minimizes both of these biases.

## 4.2. Model Form

A standard semi-log functional form is used for the hedonic models (as was discussed in Section 2.1), where the dependent variable (sales price in inflation-adjusted 1996 dollars) is transformed to its natural log form and the independent variables (e.g., square feet and acres) are not transformed. Using this form to examine the effect that views of, and distance to, wind facilities have on sales prices, the following basic model is estimated:

$$\ln(P) = \beta_0 + \beta_1 N + \sum_s \beta_2 S + \sum_k \beta_3 X + \sum_v \beta_4 \text{VIEW} + \sum_d \beta_5 \text{DISTANCE} + \varepsilon \quad (1)$$

where

P represents the inflation-adjusted sales price,

N is the spatially weighted neighbors' predicted sales price,

S is the vector of  $s$  Study Area fixed effects variables (e.g., WAOR, OKCC, etc.),

X is a vector of  $k$  home and site characteristics (e.g., acres, square feet, number of bathrooms, condition of the home, age of home, VISTA, etc.),

VIEW is a vector of  $v$  categorical view of turbine variables (e.g., MINOR, MODERATE, etc.),

DISTANCE is a vector of  $d$  categorical distance to turbine variables (e.g., less than 3000 feet, between one and three miles, etc.),

$\beta_0$  is the constant or intercept across the full sample,

$\beta_1$  is a parameter estimate for the spatially weighted neighbor's predicted sales price,

$\beta_2$  is a vector of  $s$  parameter estimates for the study area fixed effects as compared to homes sold in the Washington/Oregon (WAOR) study area,

$\beta_3$  is a vector of  $k$  parameter estimates for the home and site characteristics,

$\beta_4$  is a vector of  $v$  parameter estimates for the VIEW variables as compared to homes sold with no view of the turbines,

$\beta_5$  is a vector of  $d$  parameter estimates for the DISTANCE variables as compared to homes sold situated outside of five miles, and

$\varepsilon$  is a random disturbance term.

As such, this model, and all subsequent hedonic models, has four primary groups of parameters: variables of interest, spatial adjustments, study-area fixed effects, and home and site characteristics.

The variables of interest, VIEW and DISTANCE, are the focus of this study, and allow the investigation of the presence of Area, Scenic Vista, and Nuisance Stigmas. These variables were defined in Section 3, and are summarized in Table 8. Both VIEW and DISTANCE appear in the model together because a home's value may be affected in part by the magnitude of the view of the wind turbines, and in part by the distance from the home to those turbines, and both variables appear in the Base Model as ordered categorical values. The coefficients associated with these two vectors of variables ( $\beta_4$  and  $\beta_5$ ) represent the marginal impact of views of, and distances to, wind turbines on sales prices, as compared to a "reference" category of residential transactions, and should be ordered monotonically from low to high.<sup>51</sup> This form of variable was used to

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<sup>51</sup> "Reference category" refers to the subset of the sample to which other observations are compared, and is pertinent when using categorical or "fixed effect" variables.

impose the least structure on the underlying data.<sup>52</sup> For the purpose of the Base Model, the reference category for the DISTANCE variables are those transactions of homes that were situated outside of five miles from the nearest wind turbine. The reference category for the VIEW variables are those transactions of homes that did not have a view of the wind facility upon sale. Among the post-construction sample of homes, these reference homes are considered the least likely to be affected by the presence of the wind facilities.<sup>53</sup>

**Table 8: List of Variables of Interest Included in the Base Model**

Variable Name	Description	Type	Expected Sign
View_None	If the home sold after construction began and had no view of the turbines (Yes = 1, No = 0)	Reference	n/a
View_Minor	If the home sold after construction began and had a Minor View of the turbines (Yes = 1, No = 0)	OC	-
View_Mod	If the home sold after construction began and had a Moderate View of the turbines (Yes = 1, No = 0)	OC	-
View_Sub	If the home sold after construction began and had a Substantial View of the turbines (Yes = 1, No = 0)	OC	-
View_Extrm	If the home sold after construction began and had an Extreme View of the turbines (Yes = 1, No = 0)	OC	-
Mile_Less_0.57	If the home sold after facility "construction" and was within 0.57 miles (3000 feet) of the turbines (Yes = 1, No = 0)	OC	-
Mile_0.57to1	If the home sold after facility "construction" and was between 0.57 miles (3000 feet) and 1 mile of the turbines (Yes = 1, No = 0)	OC	-
Mile_1to3	If the home sold after facility "construction" and was between 1 and 3 miles of the turbines (Yes = 1, No = 0)	OC	-
Mile_3to5	If the home sold after facility "construction" and was between 3 and 5 miles of the turbines (Yes = 1, No = 0)	OC	-
Mile_Gtr5	If the home sold after facility "construction" and was outside 5 miles of the turbines (Yes = 1, No = 0)	Reference	n/a

*"OC" Ordered Categorical (1 = yes, 0 = no) values are interpreted in relation to the reference categorical case and are expected to have a monotonic order from low to high.*

The three stigmas are investigated through these VIEW and DISTANCE variables. Scenic Vista Stigma is investigated through the VIEW variables. Area and Nuisance Stigmas, on the other hand, are investigated through the DISTANCE variables. To distinguish between Area and

<sup>52</sup> In place of the ordered categorical DISTANCE variables, practitioners often rely on a continuous DISTANCE form (e.g., Sims et al., 2008). Similar to ordered categorical variables, continuous variables have a natural ordering, either ascending or descending, but, unlike categorical variables, these "continuous" values are on a scale. Therefore, given any two of its values  $X_1$  and  $X_2$  and a specific functional form, the ratio " $X_1/X_2$ " and the distance " $X_1 - X_2$ " have a fixed meaning. Examples of continuous variables other than DISTANCE that are commonly used include the number of square feet of living area (in 1000s) in a home (SQFT\_1000) or the acres in the parcel (ACRES). A continuous functional form of this nature "imposes structure" because practitioners must decide how price is related to the underlying variables through the selection of a specific functional relationship between the two. For instance, in the case of DISTANCE, is there a linear relationship (which would imply a similar marginal difference between two distances both near and far from the turbines), does it decay slowly as distance grows, or does it fade completely at some fixed distance? Because of the lack of literature in this area, no *a priori* expectations for which functional form is the best were established, and therefore unstructured categorical variables are used in the Base Model. Nonetheless, a continuous DISTANCE form is explored in Section 5.2.

<sup>53</sup> It is worth noting that these reference homes are situated in both rural and urban locales and therefore are not uniquely affected by influences from either setting. This further reinforces their worthiness as a reference category.

Nuisance Stigma, it is assumed that Nuisance effects are concentrated within one mile of the nearest wind turbine, while Area effects will be considered for those transactions outside of one mile. Any property value effects discovered outside of one mile and based on the DISTANCE variables are therefore assumed to indicate the presence of Area Stigma, while impacts within a mile may reflect the combination of Nuisance and Area Stigma.

The second set of variables in the Base Model - spatial adjustments - correct for the assumed presence of spatial autocorrelation in the error term ( $\epsilon$ ). It is well known that the sales price of a home can be systematically influenced by the sales prices of those homes that have sold nearby. Both the seller and the buyer use information from comparable surrounding sales to inform them of the appropriate transaction price, and nearby homes often experience similar amenities and disamenities. This lack of independence of home sale prices could bias hedonic regression results and, to help correct for this bias, a spatially (i.e., distance) weighted neighbors' sales price (N) is included in the model. Empirically, the neighbors' price has been found to be a strong (and sometimes even the strongest) predictor of home values (Leonard and Murdoch, forthcoming), and the coefficient  $\beta_1$  is expected to be positive, indicating a positive correlation between the neighbors' and subject home's sales price. A more-detailed discussion of the importance of this variable, and how it was created, is contained in Appendix G.

The third group of variables in the Base Model - study area fixed effects - control for study area influences and the differences between them. The vector's parameters  $\beta_2$  represent the marginal impact of being in any one of the study areas, as compared to a reference category. In this case, the reference category is the Washington/Oregon (WAOR) study area.<sup>54</sup> The estimated coefficients for this group of variables represent the combined effects of school districts, tax rates, crime, and other locational influences across an entire study area. Although this approach greatly simplifies the estimation of the model, because of the myriad of influences captured by these study-area fixed effects variables, interpreting the coefficient can be difficult. In general, though, the coefficients simply represent the mean difference in sales prices between the study areas and the reference study area (WAOR). These coefficients are expected to be strongly influential, indicating significant differences in sales prices across study areas.

The fourth group of variables in the Base Model are the core home and site characteristics (X), and include a range of continuous ("C"),<sup>55</sup> discrete ("D"),<sup>56</sup> binary ("B"),<sup>57</sup> and ordered categorical ("OC") variables. The specific home and site variables included in the Base Model are listed in Table 9 along with the direction of expected influence.<sup>58</sup> Variables included are age

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<sup>54</sup> Because there is no intent to focus on the coefficients of the study area fixed effect variables, the reference case is arbitrary. Further, the results for the other variables in the model are completely independent of this choice.

<sup>55</sup> See discussion in footnote 52 on previous page.

<sup>56</sup> Discrete variables, similar to continuous variables, are ordered and the distance between the values, such as  $X_1$  and  $X_2$ , have meaning, but for these variables, there are only a relatively small number of discrete values that the variable can take, for example, the number of bathrooms in a home (BATHROOMS).

<sup>57</sup> Binary variables have only two conditions: "on" or "off" (i.e., "1" or "0" respectively). Examples are whether the home has central air conditioning ("CENTRAL\_AC") or if the home is situated on a cul-de-sac ("CUL\_DE\_SAC"). The coefficients for these variables are interpreted in relation to when the condition is "off."

<sup>58</sup> For those variables with a "+" sign it is expected that as the variable increases in value (or is valued at "1" as would be the case for fixed effects variables) the price of the home will increase, and the converse is true for the variables with a "-" sign. The expected signs of the variables all follow conventional wisdom (as discussed in

of the home, home and lot size, number of bathrooms and fireplaces, the condition of the home, the quality of the scenic vista from the home, if the home has central AC, a stone exterior, and/or a finished basement, and whether the home is located in a cul-de-sac and/or on a water way.<sup>59</sup>

**Table 9: List of Home and Site Characteristics Included in the Base Model**

Variable Name	Description	Type	Expected Sign
AgeatSale	The age of the home at the time of sale in years	C	-
AgeatSale_Sqrd	The age of the home at the time of sale squared	C	+
Sqft_1000	The number of square feet of above grade finished living area (in 1000s)	C	+
Acres	The number of Acres sold with the residence	C	+
Baths	The number of Bathrooms (Full Bath = 1, Half Bath = 0.5)	D	+
ExtWalls_Stone	If the home has exterior walls of stone, brick or stucco (Yes = 1, No = 0)	B	+
CentralAC	If the home has a Central AC unit (Yes = 1, No = 0)	B	+
Fireplace	The number of fireplace openings	D	+
Cul_De_Sac	If the home is situated on a cul-de-sac (Yes = 1, No = 0)	B	+
FinBsmt	If finished basement sqft > 50% times first floor sqft (Yes = 1, No = 0)	B	+
Water_Front	If the home shares a property line with a body of water or river (Yes = 1, No = 0)	B	+
Cnd_Low	If the condition of the home is Poor (Yes = 1, No = 0)	OC	-
Cnd_BAveg	If the condition of the home is Below Average (Yes = 1, No = 0)	OC	-
Cnd_Avg	If the condition of the home is Average (Yes = 1, No = 0)	Reference	n/a
Cnd_AAvg	If the condition of the home is Above Average (Yes = 1, No = 0)	OC	+
Cnd_High	If the condition of the home is High (Yes = 1, No = 0)	OC	+
Vista_Poor	If the Scenic Vista from the home is Poor (Yes = 1, No = 0)	OC	-
Vista_BAveg	If the Scenic Vista from the home is Below Average (Yes = 1, No = 0)	OC	-
Vista_Avg	If the Scenic Vista from the home is Average (Yes = 1, No = 0)	Reference	n/a
Vista_AAvg	If the Scenic Vista from the home is Above Average (Yes = 1, No = 0)	OC	+
Vista_Prem	If the Scenic Vista from the home is Premium (Yes = 1, No = 0)	OC	+

"C" Continuous, "D" Discrete, and "B" Binary (1 = yes, 0 = no) values are interpreted in relation to "No"

"OC" Ordered Categorical (1 = yes, 0 = no) values are interpreted in relation to the reference categorical case and are expected to have a monotonic order from low to high.

Sirmans et al., 2005a), save AgeatSale and AgeatSale\_Sqrd, which are expected to be negative and positive, respectively. The magnitude of the coefficient of AgeatSale is expected to be larger than that of AgeatSale\_Sqrd indicating an initial drop in value as a home increases in age, and then an increase in value as the home becomes considerably older and more "historic."

<sup>59</sup> Some characteristics, such as whether the home had a deck, a pool, or is located on a public sewer, are not available consistently across the dataset and therefore are not incorporated into the model. Other characteristics, such as the number of bedrooms, the number of stories, or if the home had a garage, are available but are omitted from the final model because they are highly correlated with characteristics already included in the model and therefore do not add significantly to the model's explanatory power. More importantly, and as discussed in Appendix G, when their inclusion or exclusion are tested, the results are stable with those derived from the Base Model.

It should be emphasized that in the Base Hedonic Model - equation (1) - and in all subsequent models presented in Section 5, all variables of interest, spatial adjustments, and home and site characteristics are pooled, and therefore their estimates represent the average across all study areas. Ideally, one would have enough data to estimate a model at the study area level - a fully unrestricted model - rather than pooled across all areas. This fully unrestricted model form, along with 15 other model forms (with some variables restricted and others not), are discussed in detail in Appendix F. In total, these 16 different models were estimated to explore which model was the most parsimonious (had the fewest parameters), performed the best (e.g., had the highest adjusted  $R^2$  and the lowest Schwarz information criterion<sup>60</sup>), and had the most stable coefficients and standard errors. The basic pooled model described by equation (1) is found to fit that description, and that model is therefore chosen as the Base Model to which others are compared. By making this choice the effort concentrates on identifying the presence of potential property value impacts across all of the study areas in the sample as opposed to any single study area.<sup>61</sup>

Finally, to assure that the model produces the best linear unbiased parameter estimates, the underlying assumptions of Ordinary Least Squares (OLS) regression techniques must be verified:

- 1) Homoskedastic error term;
- 2) Absence of temporal serial correlation;
- 3) Reasonably limited multicollinearity; and
- 4) Appropriate controls for outliers and influencers.<sup>62</sup>

These assumptions, and the specific approaches that are used to address them, are discussed in detail in Appendix G.

### 4.3. Analysis of Results

Table 10 (on page 32) presents the results of the Base Model (equation 1).<sup>63</sup> The model performs well, with an adjusted  $R^2$  of 0.77.<sup>64</sup> The spatial adjustment coefficient ( $\beta_1$ ) of 0.29 ( $p$  value 0.00) indicates that a 10% increase in the spatially weighted neighbor's price increases the subject home's value by an average of 2.9%. The study-area fixed effects ( $\beta_2$ ) variables are all significant at the one percent level, demonstrating important differences in home valuations

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<sup>60</sup> The Schwarz information criterion measures relative parsimony between similar models (Schwarz, 1978).

<sup>61</sup> Because effects might vary between study areas, and the models estimate an average across all study areas, the full range of effects in individual study areas will go undetermined. That notwithstanding, there is no reason to suspect that effects will be completely "washed out." For that to occur, an effect in one study area would have to be positive while in another area it would have to be negative, and there is no reason to suspect that sales prices would increase because of the turbines in one community while decreasing in other communities.

<sup>62</sup> The absence of spatial autocorrelation is often included in the group of assumptions, but because it was discussed above (and in Appendix G), and is addressed directly by the variable ( $N_i$ ) included in the model, it is not included in this list.

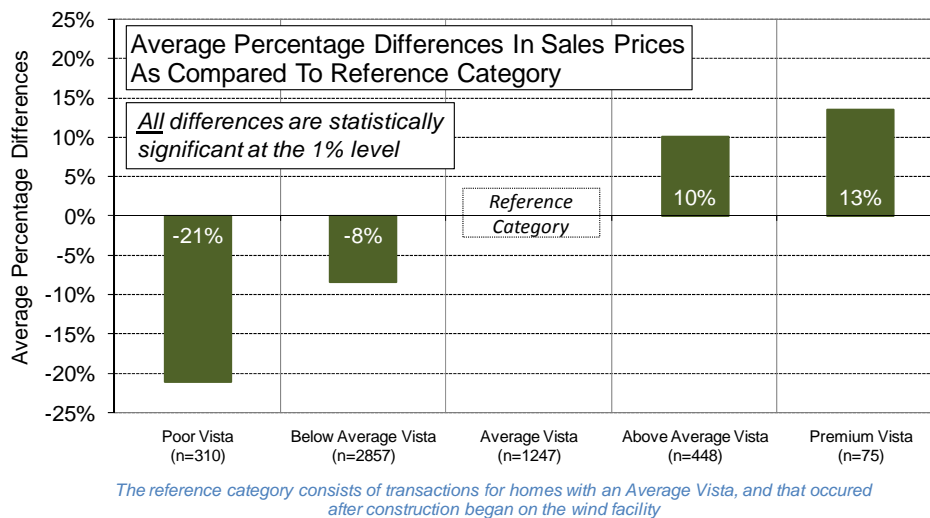
<sup>63</sup> This model and all subsequent models were estimated using the PROC REG procedure of SAS Version 9.2 TS1M0, which produces White's corrected standard errors.

<sup>64</sup> The appropriateness of the  $R^2$  of 0.77 for this research is validated by the extensive hedonic literature that precedes it (see e.g., Kroll and Priestley, 1992; Boyle and Kiel, 2001; Simons, 2006b).

between the reference study area (WAOR) and the other nine study areas.<sup>65</sup> The sign and magnitudes of the home and site characteristics are all appropriate given the *a priori* expectations, and all are statistically significant at the one percent level.<sup>66</sup>

Of particular interest are the coefficient estimates for scenic vista (VISTA) as shown in Figure 5. Homes with a POOR vista rating are found, on average, to sell for 21% less (*p* value 0.00) than homes with an AVERAGE rating, while BELOW AVERAGE homes sell for 8% less (*p* value 0.00). Conversely, homes with an ABOVE AVERAGE vista are found to sell for 10% more (*p* value 0.00) than homes with an AVERAGE vista, while PREMIUM vista homes sell for 13% more than AVERAGE homes (*p* value 0.00). Based on these results, it is evident that home buyers and sellers capitalize the quality of the scenic vista in sales prices.<sup>67</sup>

**Figure 5: Results from the Base Model for VISTA**



<sup>65</sup> The reference category WAOR study area has the highest mean and median house values in the sample (as shown in Appendix A) so the negative coefficients for all the study area fixed effect variables are appropriate.

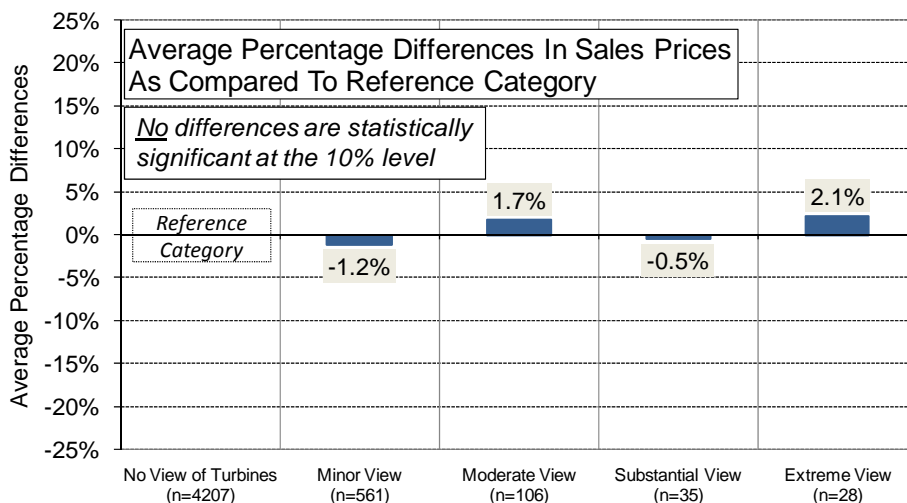
<sup>66</sup> To benchmark the results against those of other practitioners the research by Sirmans et al. (2005a; 2005b) was consulted. They conducted a meta-analysis of 64 hedonic studies carried out in multiple locations in the U.S. during multiple time periods, and investigated the coefficients of ten commonly used characteristics, seven of which were included in the model. The similarities between their mean coefficients (i.e., the average across all 64 studies) and those estimated in the present Base Model are striking. The analysis presented here estimates the effect of square feet (in 1000s) on log of sales price at 0.28 and Sirmans et al. provide an estimate of 0.34, while ACRES was similarly estimated (0.02 to 0.03, Base Model and Sirmans et al., respectively). Further, AGEATSALE (age at the time of sale) (-0.006 to -0.009), BATHROOMS (0.09 to 0.09), CENTRALAC (0.09 to 0.08), and FIREPLACE (0.11 to 0.09) all similarly compare. As a group, the Base Model estimates differ from Sirmans et al. estimates in all cases by no more than a third of the Sirmans et al. mean estimate's standard deviation. This, taken with the relatively high adjusted  $R^2$  of the Base Model, demonstrates the appropriateness of the model's specification.

<sup>67</sup> To benchmark these results they are compared to the few studies that have investigated the contribution of inland scenic vistas to sales prices. Benson et al. (2000) find that a mountain vista increases sales price by 8%, while Bourassa et al. (2004) find that wide inland vistas increase sales price by 7.6%. These both compare favorably to the 10% and 14% above average and premium rated VISTA estimates. Comparable studies for below average and poor VISTA were not found and therefore no benchmarking of those coefficients is conducted. Finally, it should again be noted that a home's scenic vista, as discussed in Section 3.2.3, was ranked without taking the presence of the wind turbines into consideration, even if those turbines were visible at the time of home sale.



Despite this finding for scenic vista, however, no statistically significant relationship is found between views of wind turbines and sales prices.<sup>68</sup> The coefficients for the VIEW parameters ( $\beta_4$ ) are all relatively small, none are statistically significant, and they are not monotonically ordered (see Figure 6). Homes with EXTREME or SUBSTANTIAL view ratings, for which the Base Model is expected to find the largest differences, sell for, on average, 2.1% more ( $p$  value 0.80) and 0.5% less ( $p$  value 0.94) than NO VIEW homes that sold in the same post-construction period. Similarly, homes with MODERATE or MINOR view ratings sell, on average, for 1.7% more ( $p$  value 0.58) and 1.2% less ( $p$  value 0.40) than NO VIEW homes, respectively. None of these coefficients are sizable, and none are statistically different from zero. These results indicate that, among this sample at least, a statistically significant relationship between views of wind turbines and residential property values is not evident. In other words, there is an absence of evidence of a Scenic Vista Stigma in the Base Model.

**Figure 6: Results from the Base Model for VIEW**

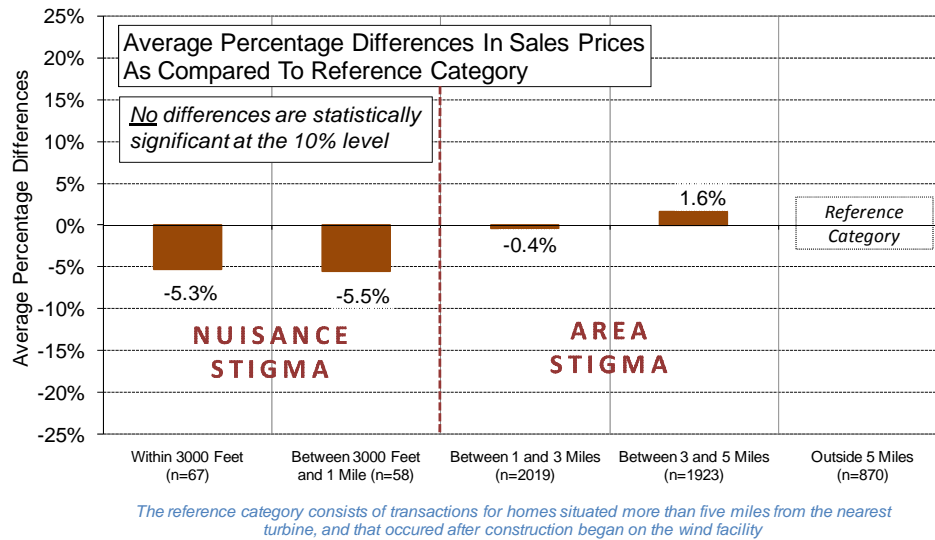


*The reference category consists of transactions for homes without a view of the turbines, and that occurred after construction began on the wind facility*

The coefficients for the DISTANCE parameters ( $\beta_5$ ) are also all relatively small and none are statistically significant (see Figure 7). Homes that are situated within 3000 feet (0.57 miles) of the nearest wind turbine, at the time of sale, are found to sell for 5.3% less ( $p$  value 0.40), on average, than homes outside of 5 miles that sold in the same “post-construction” period. Meanwhile, homes between 3000 feet and 1 mile sold for 5.5% less ( $p$  value 0.30), on average, than homes more than 5 miles away. Homes that are within 1 to 3 miles of the nearest turbine, as compared to homes outside of 5 miles, sold for essentially the same, on average (coefficient = 0.004,  $p$  value 0.80), while homes between 3 and 5 miles sold for 1.6% more ( $p$  value 0.23).

<sup>68</sup> A significance level of 10% is used throughout this report, which corresponds to a  $p$ -value at or above 0.10. Although this is more liberal than the often used 5% ( $p$ -value at or above 0.05), it was chosen to give more opportunities for effects that might be fairly weak to be considered significant.

**Figure 7: Results from the Base Model for DISTANCE**



Looking at these results as a whole, a somewhat monotonic order from low to high is found as homes are situated further away from wind facilities, but all of the coefficients are relatively small and none are statistically different from zero. This suggests that, for homes in the sample at least, there is a lack of statistical evidence that the distance from a home to the nearest wind turbine impacts sales prices, and this is true regardless of the distance band.<sup>69</sup> As such, an absence of evidence of an Area or Nuisance Stigma is found in the Base Model. That notwithstanding, the -5% coefficients for homes that sold within one mile of the nearest wind turbine require further scrutiny. Even though the differences are not found to be statistically significant, they might point to effects that exist but are too small for the model to deem statistically significant due to the relatively small number of homes in the sample within 1 mile of the nearest turbine. Alternatively, these homes may simply have been devalued even before the wind facility was erected, and that devaluation may have carried over into the post construction period (the period investigated by the Base Model). To explore these possibilities, transactions that occurred well before the announcement of the wind facility to well after construction are investigated in the Temporal Aspects Model in the following “Alternative Models” section.

<sup>69</sup> It is worth noting that the number of cases in each of these categories (e.g.,  $n = 67$  for homes inside of 3000 feet and  $n = 58$  between 3000 feet and one mile) are small, but are similar to the numbers of cases for other variables in the same model (e.g., LOW CONDITION,  $n = 69$ ; PREMIUM VISTA,  $n = 75$ ), the estimates of which were found to be significant above the 1% level.

**Table 10: Results from the Base Model**

	<b>Coef.</b>	<b>SE</b>	<b>p Value</b>	<b>n</b>
<b>Intercept</b>	7.62	0.18	0.00	
<b>Nbr LN SalePrice96 hat</b>	0.29	0.02	0.00	4,937
<b>AgeatSale</b>	-0.006	0.0004	0.00	4,937
<b>AgeatSale Sqrd</b>	0.00002	0.000003	0.00	4,937
<b>Sqft 1000</b>	0.28	0.01	0.00	4,937
<b>Acres</b>	0.02	0.00	0.00	4,937
<b>Baths</b>	0.09	0.01	0.00	4,937
<b>ExtWalls Stone</b>	0.21	0.02	0.00	1,486
<b>CentralAC</b>	0.09	0.01	0.00	2,575
<b>Fireplace</b>	0.11	0.01	0.00	1,834
<b>FinBsmnt</b>	0.08	0.02	0.00	673
<b>Cul De Sac</b>	0.10	0.01	0.00	992
<b>Water Front</b>	0.33	0.04	0.00	87
<b>Cnd Low</b>	-0.45	0.05	0.00	69
<b>Cnd BAvg</b>	-0.24	0.02	0.00	350
<b>Cnd Avg</b>	Omitted	Omitted	Omitted	2,727
<b>Cnd AAvg</b>	0.14	0.01	0.00	1,445
<b>Cnd High</b>	0.23	0.02	0.00	337
<b>Vista Poor</b>	-0.21	0.02	0.00	310
<b>Vista BAvg</b>	-0.08	0.01	0.00	2,857
<b>Vista Avg</b>	Omitted	Omitted	Omitted	1,247
<b>Vista AAvg</b>	0.10	0.02	0.00	448
<b>Vista Prem</b>	0.13	0.04	0.00	75
<b>WAOR</b>	Omitted	Omitted	Omitted	519
<b>TXHC</b>	-0.75	0.03	0.00	1,071
<b>OKCC</b>	-0.44	0.02	0.00	476
<b>IABV</b>	-0.24	0.02	0.00	605
<b>ILLC</b>	-0.09	0.03	0.00	213
<b>WIKCDC</b>	-0.14	0.02	0.00	725
<b>PASC</b>	-0.31	0.03	0.00	291
<b>PAWC</b>	-0.07	0.03	0.01	222
<b>NYMCOC</b>	-0.20	0.03	0.00	346
<b>NYMC</b>	-0.15	0.02	0.00	469
<b>Post Con NoView</b>	Omitted	Omitted	Omitted	4,207
<b>View Minor</b>	-0.01	0.01	0.40	561
<b>View Mod</b>	0.02	0.03	0.58	106
<b>View Sub</b>	-0.01	0.07	0.94	35
<b>View Extrm</b>	0.02	0.09	0.80	28
<b>Mile Less 0 57</b>	-0.05	0.06	0.40	67
<b>Mile 0 57to1</b>	-0.05	0.05	0.30	58
<b>Mile 1to3</b>	0.00	0.02	0.80	2,019
<b>Mile 3to5</b>	0.02	0.01	0.23	1,923
<b>Mile Gtr5</b>	Omitted	Omitted	Omitted	870

"Omitted" = reference category for fixed effects variables

"n" indicates number of cases in category when category = "1"

**Model Information**

<b>Model Equation Number</b>	<b>1</b>
<b>Dependent Variable</b>	<b>LN SalePrice96</b>
<b>Number of Cases</b>	<b>4937</b>
<b>Number of Predictors (k)</b>	<b>37</b>
<b>F Statistic</b>	<b>442.8</b>
<b>Adjusted R Squared</b>	<b>0.77</b>

## 5. Alternative Hedonic Models

The Base Hedonic Model presented in Section 4 found that residential property values have, on average, not been measurably affected by the presence of nearby wind facilities. To test the robustness of this result and to test for other possible impacts from nearby wind projects, the report now turns to a number of other hedonic models. These Alternative Models were created to investigate different approaches to exploring the impact of the variables of interest (#1 and #2, below) and to assess the presence of impacts that are not otherwise fully captured by the Base Model (#3 through #6, below).

- 1) **View and Distance Stability Models:** Using only post-construction transactions (the same as the Base Model) these models investigate whether the Scenic Vista Stigma (as measured with VIEW) results are independent of the Nuisance and Area Stigma results (as measured by DISTANCE) and vice versa.<sup>70</sup>
- 2) **Continuous Distance Model:** Using only post-construction transactions, this model investigates Area and Nuisance Stigmas by applying a continuous distance parameter as opposed to the categorical variables for distance used in the previous models.
- 3) **All Sales Model:** Using all transactions, this model investigates whether the results for the three stigmas change if transactions that occurred before the announcement and construction of the wind facility are included in the sample.
- 4) **Temporal Aspects Model:** Using all transactions, this model further investigates Area and Nuisance Stigmas and how they change for homes that sold more than two years pre-announcement through the period more than four years post-construction.
- 5) **Home Orientation Model:** Using only post-construction transactions, this model investigates the degree to which a home's orientation to the view of wind turbines affects sales prices.
- 6) **View and Vista Overlap Model:** Using only post-construction transactions, this model investigates the degree to which the overlap between the view of a wind facility and a home's primary scenic vista affects sales prices.

Each of these models is described in more depth in the pages that follow. Results are shown for the variables of interest only; full results are contained in Appendix H.

### 5.1. View and Distance Stability Models

The Base Model (equation 1) presented in Section 4 includes both DISTANCE and VIEW variables because a home's value might be affected in part by the magnitude of the view of a nearby wind facility and in part by the distance from the home to that facility. These two variables may be related, however, in-so-far as homes that are located closer to a wind facility are likely to have a more-dominating view of that facility. To explore the degree to which these two sets of variables are independent of each other (i.e. not collinear) and to further test the robustness of the Base Model results two alternative hedonic models are run, each of which includes only one of the sets of parameters (DISTANCE or VIEW). Coefficients from these models are then compared to the Base Model results.

---

<sup>70</sup> Recall that the qualitative VIEW variable incorporated the visible distance to the nearest wind facility.

### 5.1.1. Dataset and Model Form

The same dataset is used as in the Base Model, focusing again on post-construction transactions ( $n = 4,937$ ). To investigate DISTANCE effects alone the following model is estimated:

$$\ln(P) = \beta_0 + \beta_1 N + \sum_s \beta_2 S + \sum_k \beta_3 X + \sum_d \beta_5 \text{DISTANCE} + \varepsilon \quad (2)$$

where

$P$  represents the inflation-adjusted sales price,

$N$  is the spatially weighted neighbors' predicted sales price,

$S$  is the vector of  $s$  Study Area fixed effects variables (e.g., WAOR, OKCC, etc.),

$X$  is a vector of  $k$  home and site characteristics (e.g., acres, square feet, number of bathrooms, condition of the home, age of home, VISTA, etc.),

$\text{DISTANCE}$  is a vector of  $d$  categorical distance variables (e.g., less than 3000 feet, between one and three miles, etc.),

$\beta_0$  is the constant or intercept across the full sample,

$\beta_1$  is a parameter estimate for the spatially weighted neighbor's predicted sales price,

$\beta_2$  is a vector of  $s$  parameter estimates for the study area fixed effects as compared to transactions of homes in the WAOR study area,

$\beta_3$  is a vector of  $k$  parameter estimates for the home and site characteristics,

$\beta_5$  is a vector of  $d$  parameter estimates for the DISTANCE variables as compared to transactions of homes situated outside of five miles, and

$\varepsilon$  is a random disturbance term.

The parameters of primary interest are  $\beta_5$ , which represent the marginal differences between home values at various distances from the wind turbines as compared to the reference category of homes outside of five miles. These coefficients can then be compared to the same coefficients estimated from the Base Model.

Alternatively, to investigate the VIEW effects alone, the following model is estimated:

$$\ln(P) = \beta_0 + \beta_1 N + \sum_s \beta_2 S + \sum_k \beta_3 X + \sum_v \beta_4 \text{VIEW} + \varepsilon \quad (3)$$

where

$\text{VIEW}$  is a vector of  $v$  categorical view variables (e.g., MINOR, MODERATE, etc.),

$\beta_4$  is a vector of  $v$  parameter estimates for the VIEW variables, and

all other components are as defined in equation (2).

The parameters of primary interest in this model are  $\beta_4$ , which represent the marginal differences between home values for homes with varying views of wind turbines at the time of sale as compared to the reference category of homes without a view of those turbines. Again, these coefficients can then be compared to the same coefficients estimated from the Base Model.

Our expectation for both of the models described here is that the results will not be dramatically different from the Base Model, given the distribution of VIEW values across the DISTANCE values, and vice versa, as shown in Table 11. Except for EXTREME view, which is

concentrated inside of 3000 feet, all view ratings are adequately distributed among the distance categories.

**Table 11: Frequency Crosstab of VIEW and DISTANCE Parameters**

	Inside 3000 Feet	Between 3000 Feet and 1 Mile	Between 1 and 3 Miles	Between 3 and 5 Miles	Outside 5 Miles	Total
No View	6	12	1653	1695	841	4207
Minor View	14	24	294	202	27	561
Moderate View	8	13	62	21	2	106
Substantial View	11	9	10	5	0	35
Extreme View	28	0	0	0	0	28
<b>TOTAL</b>	<b>67</b>	<b>58</b>	<b>2019</b>	<b>1923</b>	<b>870</b>	<b>4937</b>

### 5.1.2. Analysis of Results

Summarized results for the variables of interest from the Base Model and the two Alternative Stability Models are presented in Table 12. (For brevity, the full set of results for the models is not shown in Table 12, but is instead included in Appendix H.) The adjusted R<sup>2</sup> for the View and Distance Stability Models is the same as for the Base Model, 0.77. All study area, spatial adjustment, and home and site characteristics are significant at or above the one percent level and are similar in magnitude to the estimates presented earlier for the Base Model.

The DISTANCE and VIEW coefficients,  $\beta_5$  and  $\beta_4$ , are stable, changing no more than 3%, with most (7 out of 8) not experiencing a change greater than 1%. In all cases, changes to coefficient estimates for the variables of interest are considerably less than the standard errors. Based on these results, there is confidence that the correlation between the VIEW and DISTANCE variables is not responsible for the findings and that these two variables are adequately independent to be included in the same hedonic model regression. As importantly, no evidence of Area, Scenic Vista, or Nuisance Stigma is found in the sample, as none of the VIEW or DISTANCE variables are found to be statistically different from zero.

**Table 12: Results from Distance and View Stability Models**

Variables of Interest	n	Base Model			Distance Stability			View Stability		
		Coef	SE	p Value	Coef	SE	p Value	Coef	SE	p Value
No View	4207	Omitted	Omitted	Omitted				Omitted	Omitted	Omitted
Minor View	561	-0.01	0.01	0.39				-0.02	0.01	0.24
Moderate View	106	0.02	0.03	0.57				0.00	0.03	0.90
Substantial View	35	-0.01	0.07	0.92				-0.04	0.06	0.45
Extreme View	28	0.02	0.09	0.77				-0.03	0.06	0.58
Inside 3000 Feet	67	-0.05	0.06	0.31	-0.04	0.04	0.25			
Between 3000 Feet and 1 Mile	58	-0.05	0.05	0.20	-0.06	0.05	0.17			
Between 1 and 3 Miles	2019	0.00	0.02	0.80	-0.01	0.02	0.71			
Between 3 and 5 Miles	1923	0.02	0.01	0.26	0.01	0.01	0.30			
Outside 5 Miles	870	Omitted	Omitted	Omitted	Omitted	Omitted	Omitted			

"Omitted" = reference category for fixed effects variables. "n" indicates number of cases in category when category = "1"

#### Model Information

Model Equation Number	1	2	3
Dependent Variable	LN_SalePrice96	LN_SalePrice96	LN_SalePrice96
Number of Cases	4937	4937	4937
Number of Predictors (k)	37	33	33
F Statistic	442.8	496.7	495.9
Adjusted R Squared	0.77	0.77	0.77

## 5.2. Continuous Distance Model

The potential impact of wind facilities on residential property values based on Area and Nuisance effects was explored with the Base Model by using five ordered categorical DISTANCE variables. This approach was used in order to impose the least restriction on the functional relationship between distance and property values (as discussed in footnote 52 on page 25). The literature on environmental disamenities, however, more commonly uses a continuous distance form (e.g., Sims et al., 2008), which imposes more structure on this relationship. To be consistent with the literature and to test if a more rigid structural relationship might uncover an effect that is not otherwise apparent with the five distance categories used in the Base Model, a hedonic model that relies upon a continuous distance variable is presented here. One important benefit of this model is that a larger amount of data (e.g.,  $n = 4,937$ ) is used to estimate the continuous DISTANCE coefficient then was used to estimate any of the individual categorical estimates in the Base Model (e.g.,  $n = 67$  inside 3000 feet,  $n = 2019$  between one and three miles). The Continuous Distance Model therefore provides an important robustness test to the Base Model results.

### 5.2.1. Dataset and Model Form

A number of different functional forms can be used for a continuous DISTANCE variable, including linear, inverse, cubic, quadratic, and logarithmic. Of the forms that are considered, an inverse function seemed most appropriate.<sup>71</sup> Inverse functions are used when it is assumed that any effect is most pronounced near the disamenity and that those effects fade asymptotically as distance increases. This form has been used previously in the literature (e.g., Leonard et al., 2008) to explore the impact of disamenities on home values, and is calculated as follows:

$$\text{InvDISTANCE} = 1 / \text{DISTANCE} \quad (4)$$

where

DISTANCE is the distances to the nearest turbine from each home as calculated at the time of sale for homes that sold in the post-construction period.

For the purpose of the Continuous Distance Model, the same dataset is used as in the Base Model, focusing again on post-construction transactions ( $n = 4,937$ ). InvDISTANCE has a maximum of 6.67 (corresponding to homes that were 0.15 miles, or roughly 800 feet, from the nearest wind turbine), a minimum of 0.09 (corresponding to a distance of roughly 11 miles), and a mean of 0.38 (corresponding to a distance of 2.6 miles). This function was then introduced into the hedonic model in place of the DISTANCE categorical variables as follows:

$$\ln(P) = \beta_0 + \beta_1 N + \sum_s \beta_2 S + \sum_k \beta_3 X + \sum_v \beta_4 \text{VIEW} + \beta_5 \text{InvDISTANCE} + \varepsilon \quad (5)$$

where

InvDISTANCE<sub>i</sub> is the inverse of the distance to the nearest turbine,

$\beta_5$  is a parameter estimate for the inverse of the distance to the nearest turbine, and

---

<sup>71</sup> The other distance functions (e.g., linear, quadratic, cubic & logarithmic) were also tested. Additionally, two-part functions with interactions between continuous forms (e.g., linear) and categorical (e.g., less than one mile) were investigated. Results from these models are briefly discussed below in footnote 72.

all other components are as defined in equation (1).

The coefficient of interest in this model is  $\beta_5$ , which, if effects exist, would be expected to be negative, indicating an adverse effect from proximity to the wind turbines.

### 5.2.2. Analysis of Results

Results for the variables of interest in the Continuous Distance Model and the Base Model are shown in Table 13. (For brevity, the full set of results for the model is not shown in Table 13, but is instead included in Appendix H.) The model performs well with an adjusted  $R^2$  of 0.77. All study area, spatial adjustment, and home and site characteristics are significant at the one percent level. The coefficients for VIEW are similar to those found in the Base Model, demonstrating stability in results, and none are statistically significant. These results support the previous findings of a lack of evidence of a Scenic Vista Stigma.

Our focus variable InvDISTANCE produces a coefficient ( $\beta_5$ ) that is slightly negative at -1%, but that is not statistically different from zero ( $p$  value 0.41), implying again that there is no statistical evidence of a Nuisance Stigma effect nor an Area Stigma effect and confirming the results obtained in the Base Model.<sup>72</sup>

**Table 13: Results from Continuous Distance Model**

Variables of Interest	Base Model				Continuous Distance			
	Coef	SE	p Value	<i>n</i>	Coef	SE	p Value	<i>n</i>
No View	Omitted	Omitted	Omitted	4,207	Omitted	Omitted	Omitted	4,207
Minor View	-0.01	0.01	0.39	561	-0.01	0.01	0.32	561
Moderate View	0.02	0.03	0.57	106	0.01	0.03	0.77	106
Substantial View	-0.01	0.07	0.92	35	-0.02	0.07	0.64	35
Extreme View	0.02	0.09	0.77	28	0.01	0.10	0.85	28
Inside 3000 Feet	-0.05	0.06	0.31	67				
Between 3000 Feet and 1 Mile	-0.05	0.05	0.20	58				
Between 1 and 3 Miles	0.00	0.02	0.80	2,019				
Between 3 and 5 Miles	0.02	0.01	0.26	1,923				
Outside 5 Miles	Omitted	Omitted	Omitted	870				
InvDISTANCE					-0.01	0.02	0.41	4,937

"Omitted" = reference category for fixed effects variables. "n" = number of cases in category when category = "1"

#### Model Information

Model Equation Number	1
Dependent Variable	LN_SalePrice96
Number of Cases	4937
Number of Predictors (k)	37
F Statistic	442.8
Adjusted R Squared	0.77

5
LN_SalePrice96
4937
34
481.3
0.77

### 5.3. All Sales Model

The Base Model presented earlier relied on only those transactions that occurred after the construction of the relevant wind facility. This approach, however, leaves open two key questions. First, it is possible that the property values of all of the post-construction homes in the

<sup>72</sup> As mentioned in footnote 71 on page 36, a number of alternative forms of the continuous distance function were also explored, including two-part functions, with no change in the results presented here. In all cases the resulting continuous distance function was not statistically significant.



sample have been affected by the presence of a wind facility, and therefore that the reference homes in the Base Model (i.e., those homes outside of five miles with no view of a wind turbine) are an inappropriate comparison group because they too have been impacted.<sup>73</sup> Using only those homes that sold before the announcement of the wind facility (pre-announcement) as the reference group would, arguably, make for a better comparison because the sales price of those homes are not plausibly impacted by the presence of the wind facility.<sup>74</sup> Second, the Base Model does not consider homes that sold in the post-announcement but pre-construction period, and previous research suggests that property value effects might be very strong during this period, during which an assessment of actual impacts is not possible and buyers and sellers may take a more-protective and conservative stance (Wolsink, 1989). This subsection therefore presents the results of a hedonic model that uses the full set of transactions in the dataset, pre- and post-construction.

### 5.3.1. Dataset and Model Form

Unlike the Base Model, in this instance the full set of 7,459 residential transactions is included. The following model is then estimated:

$$\ln(P) = \beta_0 + \beta_1 N + \sum_s \beta_2 S + \sum_k \beta_3 X + \sum_v \beta_4 \text{VIEW} + \sum_d \beta_5 \text{DISTANCE} + \varepsilon \quad (6)$$

where

VIEW is a vector of  $v$  categorical view variables (e.g., NONE, MINOR, MODERATE, etc.), DISTANCE is a vector of  $d$  categorical distance variables (e.g., less than 3000 feet, between one and three miles, outside of five mile, etc.),

$\beta_4$  is a vector of  $v$  parameter estimates for the VIEW variables as compared to pre-construction transactions,

$\beta_5$  is a vector of  $d$  parameter estimates for the DISTANCE variables as compared to pre-announcement transactions, and

all other components are as defined in equation (1).

It is important to emphasize that the VIEW and DISTANCE parameters in equation (6) have different reference categories than they do in the Base Model - equation (1). In the Base Model, DISTANCE and VIEW are estimated in the post-construction period in reference to homes that sold outside of five miles and with no view of the turbines respectively.<sup>75</sup> In the All Sales Model, on the other hand, the coefficients for VIEW ( $\beta_4$ ) are estimated in reference to all pre-construction transactions (spanning the pre-announcement and post-announcement-pre-construction periods) and the coefficients for DISTANCE ( $\beta_5$ ) are estimated in reference to all pre-announcement transactions. In making a distinction between the reference categories for VIEW and DISTANCE, it is assumed that awareness of the view of turbines and awareness of

<sup>73</sup> This might be the case if there is an Area Stigma that includes the reference homes.

<sup>74</sup> As discussed in footnote 47 on page 19, it is conceivable that awareness might occur prior to the “announcement” date used for this analysis. If true, this bias is likely to be sporadic in nature and less of an issue in this model, when all pre-announcement transactions are pooled (e.g., both transactions near and far away from where the turbines were eventually located) than in models presented later (e.g., temporal aspects model). Nonetheless, if present, this bias may weakly draw down the pre-announcement reference category.

<sup>75</sup> See Section 4.1 and also footnote 51 on page 24 for more information on why the post-construction dataset and five-mile-no-view homes reference category are used in the Base Model.

the distance from them might not occur at the same point in the development process. Specifically, it is assumed that VIEW effects largely occur after the turbines are erected, in the post-construction period, but that DISTANCE effects might occur in the post-announcement-pre-construction timeframe. For example, after a wind facility is announced, it is not atypical for a map of the expected locations of the turbines to be circulated in the community, allowing home buyers and sellers to assess the distance of the planned facility from homes. Because of this assumed difference in when awareness begins for VIEW and DISTANCE, the DISTANCE variable is populated for transactions occurring in the post-announcement-pre-construction period as well as the post-construction period (see Table 14 below), but the VIEW variable is populated only for transactions in the post-construction period – as they were in the Base Model.<sup>76</sup>

**Table 14: Frequency Summary for DISTANCE in All Sales Model**

	< 0.57 Miles	0.57 - 1 Miles	1 - 3 Miles	3 - 5 Miles	> 5 Miles	Total
Post-Construction	67	58	2019	1923	870	4937
Post-Announcement-Pre-Construction	13	7	340	277	130	767
<b>TOTAL</b>	<b>80</b>	<b>65</b>	<b>2359</b>	<b>2200</b>	<b>1000</b>	<b>5704</b>

One beneficial consequence of the differences in reference categories for the VIEW and DISTANCE variables in this model, as opposed to the Base Model, is that this model can accommodate all of the possible VIEW and DISTANCE categories, including NO VIEW transactions and transactions of homes outside of five miles. Because of the inclusion of these VIEW and DISTANCE categories, the tests to investigate Area, Scenic Vista, and Nuisance Stigmas are slightly different in this model than in the Base Model. For Area Stigma, for example, how homes with no view of the turbines fared can now be tested; if they are adversely affected by the presence of the wind facility, then this would imply a pervasive Area Stigma impact. For Scenic Vista Stigma, the VIEW coefficients (MINOR, MODERATE, etc.) can be compared (using a *t*-Test) to the NO VIEW results; if they are significantly different, a Scenic Vista Stigma would be an obvious culprit. Finally, for Nuisance Stigma, the DISTANCE coefficients inside of one mile can be compared (using a *t*-Test) to those outside of five miles; if there is a significant difference between these two categories of homes, then homes are likely affected by their proximity to the wind facility.

### 5.3.2. Analysis of Results

Results for the variables of interest for this hedonic model are summarized in Table 15, and Base Model results are shown for comparison purposes. (For brevity, the full set of results for the model is not shown in Table 15, but is instead included in Appendix H.) The adjusted R<sup>2</sup> for the model is 0.75, down slightly from 0.77 for the Base Model, and indicating that this model has slightly more difficulty (i.e. less explanatory power) modeling transactions that occurred pre-

<sup>76</sup> It is conceivable that VIEW effects could occur before the turbines are constructed. In some cases, for example, developers will simulate what the project will look like after construction during the post-announcement but pre-construction timeframe. In these situations, home buyers and sellers might adjust home values accordingly based on the expected views of turbines. It is assumed, however, that such adjustments are likely to be reasonably rare, and VIEW effects are therefore estimated using only post-construction sales.

construction.<sup>77</sup> All study area, spatial adjustment, and home and site characteristics are significant at or above the one percent level and are similar in sign and magnitude to the estimates derived from the post-construction Base Model.

The VIEW coefficients ( $\beta_4$ ) are clearly affected by the change in reference category. All of the VIEW parameter estimates are higher than the Base Model estimates for the same categories. Of particular interest is the NO VIEW coefficient, which represents the values of homes without a view of the turbines and that sold in the post-construction period, as compared to the mean value of homes that sold in the pre-construction period, all else being equal. These homes, on average, are estimated to sell for 2% ( $p$  value 0.08) more than similar pre-construction homes. If an Area Stigma existed, a negative coefficient for these NO VIEW homes would be expected. Instead, a positive and statistically significant coefficient is found.<sup>78</sup> It is outside the ability of this study to determine whether the increase is directly related to the wind turbines, or whether some other factor is impacting these results, but in either instance, no evidence of a pervasive Area Stigma associated with the presence of the wind facilities is found.

To test for the possibility of Scenic Vista Stigma, the coefficients for MINOR, MODERATE, SUBSTANTIAL, and EXTREME views can be compared to the NO VIEW coefficient using a simple  $t$ -Test. Table 16 presents these results. As shown, no significant difference is found for any of the VIEW coefficients when compared to NO VIEW transactions. This reinforces the findings earlier that, within the sample at least, there is no evidence of a Scenic Vista Stigma.

The DISTANCE parameter estimates ( $\beta_5$ ) are also found to be affected by the change in reference category, and all are lower than the Base Model estimates for the same categories. This result likely indicates that the inflation-adjusted mean value of homes in the pre-announcement period is slightly higher, on average, than for those homes sold outside of five miles in the post-construction period. This difference could be attributed to the inaccuracy of the inflation index, a pervasive effect from the wind turbines, or to some other cause. Because the coefficients are not systematically statistically significant, however, this result is not pursued further. What is of interest, however, is the negative 8% estimate for homes located between 3000 feet and one mile of the nearest wind turbine ( $p$  value 0.03). To correctly interpret this result, and to compare it to the Base Model, one needs to discern if this coefficient is significantly different from the estimate for homes located outside of five miles, using a  $t$ -Test.

The results of this  $t$ -Test are shown in Table 17. The coefficient differences are found to be somewhat monotonically ordered. Moving from homes within 3000 feet (-0.06,  $p$  value 0.22), and between 3000 feet and one mile (-0.08,  $p$  value 0.04), to between one and three miles (0.00,  $p$  value 0.93) and between three and five miles (0.01,  $p$  value 0.32) the DISTANCE coefficients are found to generally increase. Nonetheless, none of these coefficients are statistically significant except one, homes that sold between 3000 feet and one mile. The latter finding suggests the possibility of Nuisance Stigma. It is somewhat unclear why an effect would be found in this model, however, when one was not evident in the Base Model. The most likely

---

<sup>77</sup> This slight change in performance is likely due to the inaccuracies of home and site characteristics and the inflation adjustment for homes that sold in the early part of the study period. This is discussed in more detail in footnote 50 on page 23.

<sup>78</sup> For more on the significance level used for this report, see footnote 68 on page 30.

explanation is that the additional homes that are included in this model, specifically those homes that sold post-announcement but pre-construction, are driving the results. A thorough investigation of these “temporal” issues is provided in the next subsection.

In summation, no evidence is found of an Area or Scenic Vista Stigma in this alternative hedonic model, but some limited not-conclusive evidence of a Nuisance Stigma is detected. To further explore the reliability of this latter result, the analysis now turns to the Temporal Aspects Model.

**Table 15: Results from All Sales Model**

Variables of Interest	Base Model				All Sales			
	Coef	SE	p Value	n	Coef	SE	p Value	n
Pre-Construction Sales	n/a	n/a	n/a	n/a	Omitted	Omitted	Omitted	2,522
No View	Omitted	Omitted	Omitted	4,207	0.02	0.01	0.08	4,207
Minor View	-0.01	0.01	0.39	561	0.00	0.02	0.77	561
Moderate View	0.02	0.03	0.57	106	0.03	0.03	0.41	106
Substantial View	-0.01	0.07	0.92	35	0.03	0.07	0.53	35
Extreme View	0.02	0.09	0.77	28	0.06	0.08	0.38	28
Inside 3000 Feet	-0.05	0.06	0.31	67	-0.06	0.05	0.18	80
Between 3000 Feet and 1 Mile	-0.05	0.05	0.20	58	-0.08	0.05	0.03	65
Between 1 and 3 Miles	0.00	0.02	0.80	2,019	0.00	0.01	0.80	2,359
Between 3 and 5 Miles	0.02	0.01	0.26	1,923	0.01	0.01	0.59	2,200
Outside 5 Miles	Omitted	Omitted	Omitted	870	0.00	0.02	0.78	1,000
Pre-Announcement Sales	n/a	n/a	n/a	n/a	Omitted	Omitted	Omitted	1,755

"Omitted" = reference category for fixed effects variables. "n" = number of cases in category when category = "1"

**Model Information**

Model Equation Number	1
Dependent Variable	LN_SalePrice96
Number of Cases	4937
Number of Predictors (k)	37
F Statistic	442.8
Adjusted R Squared	0.77

6
LN_SalePrice96
7459
39
579.9
0.75

**Table 16: Results from Equality Test of VIEW Coefficients in the All Sales Model**

	No View	Minor View	Moderate View	Substantial View	Extreme View
n	4,207	561	106	35	28
Coefficient	0.02	0.00	0.03	0.03	0.06
Coefficient Difference *	Reference	-0.02	0.00	0.01	0.04
Variance	0.0001	0.0003	0.0009	0.0030	0.0050
Covariance	n/a	0.00011	0.00010	0.00009	0.00008
Df	n/a	7419	7419	7419	7419
t -Test	n/a	-1.20	0.17	0.23	0.58
Significance	n/a	0.23	0.87	0.82	0.57

\* Differences are rounded to the nearest second decimal place.

"n" = number of cases in category when category = "1"

**Table 17: Results from Equality Test of DISTANCE Coefficients in the All Sales Model**

	Inside 3000 Feet	Between 3000 Feet and 1 Mile	Between 1 and 3 Miles	Between 3 and 5 Miles	Outside 5 Miles
<i>n</i>	80	65	2,359	2,200	1,000
Coefficient	-0.06	-0.08	0.00	0.01	0.00
Coefficient Difference *	-0.05	-0.08	0.00	0.01	Reference
Variance	0.0019	0.0015	0.0002	0.0002	0.0003
Covariance	0.00010	0.00013	0.00013	0.00015	n/a
Df	7419	7419	7419	7419	n/a
<i>t</i> Test	-1.23	-2.06	0.09	1.00	n/a
Significance	0.22	0.04	0.93	0.32	n/a

\* Differences are rounded to the nearest second decimal place.

"n" = number of cases in category when category = "1"

## 5.4. Temporal Aspects Model

Based on the results of the All Sales Model, a more thorough investigation of how Nuisance and Area Stigma effects might change throughout the wind project development period is warranted. As discussed previously, there is some evidence that property value impacts may be particularly strong after the announcement of a disamenity, but then may fade with time as the community adjusts to the presence of that disamenity (e.g., Wolsink, 1989). The Temporal Aspects Model presented here allows for an investigation of how the different periods of the wind project development process affect estimates for the impact of DISTANCE on sales prices.

### 5.4.1. Dataset and Model Form

Here the full set of 7,459 residential transactions is used, allowing an exploration of potential property value impacts (focusing on the DISTANCE variable) throughout time, including in the pre-construction period. The following model is then estimated:

$$\ln(P) = \beta_0 + \beta_1 N + \sum_s \beta_2 S + \sum_k \beta_3 X + \sum_v \beta_4 \text{VIEW} + \sum_y \beta_5 (\text{DISTANCE} \cdot \text{PERIOD}) + \varepsilon \quad (7)$$

where

DISTANCE is a vector of categorical distance variables (e.g., less than one mile, between one and three miles, etc.),

PERIOD is a vector of categorical development period variables (e.g., after announcement and before construction, etc.),

$\beta_5$  is a vector of  $\gamma$  parameter estimates for each DISTANCE and PERIOD category as compared to the transactions more than two years before announcement and outside of five miles, and all other components are as defined in equation (1).

The PERIOD variable contains six different options:

- 1) More than two years before announcement;
- 2) Less than two years before announcement;
- 3) After announcement but before construction;
- 4) Less than two years after construction;
- 5) Between two and four years after construction; and

6) More than four years after construction.

In contrast to the Base Model, the two DISTANCE categories inside of one mile are collapsed into a single “less than one mile” group. This approach increases the number of transactions in each crossed subcategory of data, and therefore enhances the stability of the parameter estimates and decreases the size of the standard errors, thus providing an increased opportunity to discover statistically significant effects. Therefore, in this model the DISTANCE variable contains four different options:

- 1) Less than one mile;
- 2) Between one and three miles;
- 3) Between three and five miles; and
- 4) Outside of five miles.<sup>79</sup>

The number of transactions in each of the DISTANCE and PERIOD categories is presented in Table 18.

The coefficients of interest are  $\beta_5$ , which represent the vector of marginal differences between homes sold at various distances from the wind facility (DISTANCE) during various periods of the development process (PERIOD) as compared to the reference group. The reference group in this model consists of transactions that occurred more than two years before the facility was announced for homes that were situated more than five miles from where the turbines were ultimately constructed. It is assumed that the value of these homes would not be affected by the future presence of the wind facility. The VIEW parameters, although included in the model, are not interacted with PERIOD and therefore are treated as controlling variables.<sup>80</sup>

Although the comparisons of these categorical variables between different DISTANCE and PERIOD categories is be interesting, it is the comparison of coefficients within each PERIOD and DISTANCE category that is the focus of this section. Such comparisons, for example, allow one to compare how the average value of homes inside of one mile that sold two years before announcement compare to the average value of homes inside of one mile that sold in the post-announcement-pre-construction period. For this comparison, a *t*-Test similar to that in the All Sales Model is used.

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<sup>79</sup> For homes that sold in the pre-construction time frame, no turbines yet existed, and therefore DISTANCE is created using a proxy: the Euclidian distance to where the turbines were eventually constructed. This approach introduces some bias when there is more than one facility in the study area. Conceivably, a home that sold in the post-announcement-pre-construction period of one wind facility could also be assigned to the pre-announcement period of another facility in the same area. For this type of sale, it is not entirely clear which PERIOD and DISTANCE is most appropriate, but every effort was made to apply the sale to the wind facility that was most likely to have an impact. In most cases this meant choosing the closest facility, but in some cases, when development periods were separated by many years, simply the earliest facility was chosen. In general, any bias created by these judgments is expected to be minimal because, in the large majority of cases, the development process in each study area was more-or-less continuous and focused in a specific area rather than being spread widely apart.

<sup>80</sup> As discussed earlier, the VIEW variable was considered most relevant for the post-construction period, so delineations based on development periods that extended into the pre-construction phase were unnecessary. It is conceivable, however, that VIEW effects vary in periods following construction, such as in the first two years or after that. Although this is an interesting question, the numbers of cases for the SUBSTANTIAL and EXTREME ratings – even if combined – when divided into the temporal periods were too small to be fruitful for analysis.

**Table 18: Frequency Crosstab of DISTANCE and PERIOD**

	More Than 2 Years Before Announcement	Less Than 2 Years Before Announcement	After Announcement Before Construction	Less Than 2 Years After Construction	Between 2 and 4 Years After Construction	More Than 4 Years After Construction	Total
Less Than 1 Mile	38	40	20	39	45	43	225
Between 1 and 3 Miles	283	592	340	806	502	709	3,232
Between 3 and 5 Miles	157	380	277	572	594	757	2,737
Outside of 5 Miles	132	133	130	218	227	425	1,265
<b>TOTAL</b>	<b>610</b>	<b>1,145</b>	<b>767</b>	<b>1,635</b>	<b>1,368</b>	<b>1,934</b>	<b>7,459</b>

### 5.4.2. Analysis of Results

Results for the variables of interest for this hedonic model are presented in Table 19; as with previous models, the full set of results is contained in Appendix H. Similar to the All Sales Model discussed in the previous section, the adjusted  $R^2$  for the model is 0.75, down slightly from 0.77 for the Base Model, and indicating that this model has slightly more difficulty (i.e., less explanatory power) modeling transactions that occurred before wind facility construction. All study area, spatial adjustment, and home and site characteristics are significant at or above the one percent level, are of the appropriate sign, and are similar in magnitude to the estimates derived from the post-construction Base Model.

All of the DISTANCE / PERIOD interaction coefficients for distances outside of one mile are relatively small ( $-0.04 < \beta_5 < 0.02$ ) and none are statistically significant. This implies that there are no statistically significant differences in property values between the reference category homes – homes sold more than two years before announcement that were situated outside of five miles from where turbines were eventually erected – and any of the categories of homes that sold outside of one mile at any other period in the wind project development process. These comparisons demonstrate, arguably more directly than any other model presented in this report that Area Stigma effects likely do not exist in the sample.

The possible presence of a Nuisance Stigma is somewhat harder to discern. For homes that sold inside of one mile of the nearest wind turbine, in three of the six periods there are statistically significant negative differences between average property values when compared to the reference category. Transactions completed more than two years before facility announcement are estimated to be valued at 13% less ( $p$  value 0.02) than the reference category, transactions less than two years before announcement are 10% lower ( $p$  value 0.06), and transactions after announcement but before construction are 14% lower ( $p$  value 0.04). For other periods, however, these marginal differences are considerably smaller and are not statistically different from the reference category. Sales prices in the first two years after construction are, on average, 9% less ( $p$  value 0.15), those occurring between three and four years following construction are, on average, 1% less ( $p$  value 0.86), and those occurring more than four years after construction are, on average, 7% less ( $p$  value 0.37).

**Table 19: Results from Temporal Aspects Model**

Variables of Interest		Temporal Aspects			
		Coef	SE	p Value	n
Inside 1 Mile	More Than 2 Years Before Announcement	-0.13	0.06	0.02	38
	Less Than 2 Years Before Announcement	-0.10	0.05	0.06	40
	After Announcement Before Construction	-0.14	0.06	0.04	21
	2 Years After Construction	-0.09	0.07	0.11	39
	Between 2 and 4 Years After Construction	-0.01	0.06	0.85	44
	More Than 4 Years After Construction	-0.07	0.08	0.22	42
Between 1-3 Miles	More Than 2 Years Before Announcement	-0.04	0.03	0.18	283
	Less Than 2 Years Before Announcement	0.00	0.03	0.91	592
	After Announcement Before Construction	-0.02	0.03	0.54	342
	2 Years After Construction	0.00	0.03	0.90	807
	Between 2 and 4 Years After Construction	0.01	0.03	0.78	503
	More Than 4 Years After Construction	0.00	0.03	0.93	710
Between 3-5 Miles	More Than 2 Years Before Announcement	0.00	0.04	0.92	157
	Less Than 2 Years Before Announcement	0.00	0.03	0.97	380
	After Announcement Before Construction	0.00	0.03	0.93	299
	2 Years After Construction	0.02	0.03	0.55	574
	Between 2 and 4 Years After Construction	0.01	0.03	0.65	594
	More Than 4 Years After Construction	0.01	0.03	0.67	758
Outside 5 Miles	More Than 2 Years Before Announcement	Omitted	Omitted	Omitted	132
	Less Than 2 Years Before Announcement	-0.03	0.04	0.33	133
	After Announcement Before Construction	-0.03	0.03	0.39	105
	2 Years After Construction	-0.03	0.03	0.44	215
	Between 2 and 4 Years After Construction	0.03	0.03	0.44	227
	More Than 4 Years After Construction	0.01	0.03	0.73	424

"Omitted" = reference category for fixed effects variables.

"n" indicates number of cases in category when category = "1"

**Model Information**

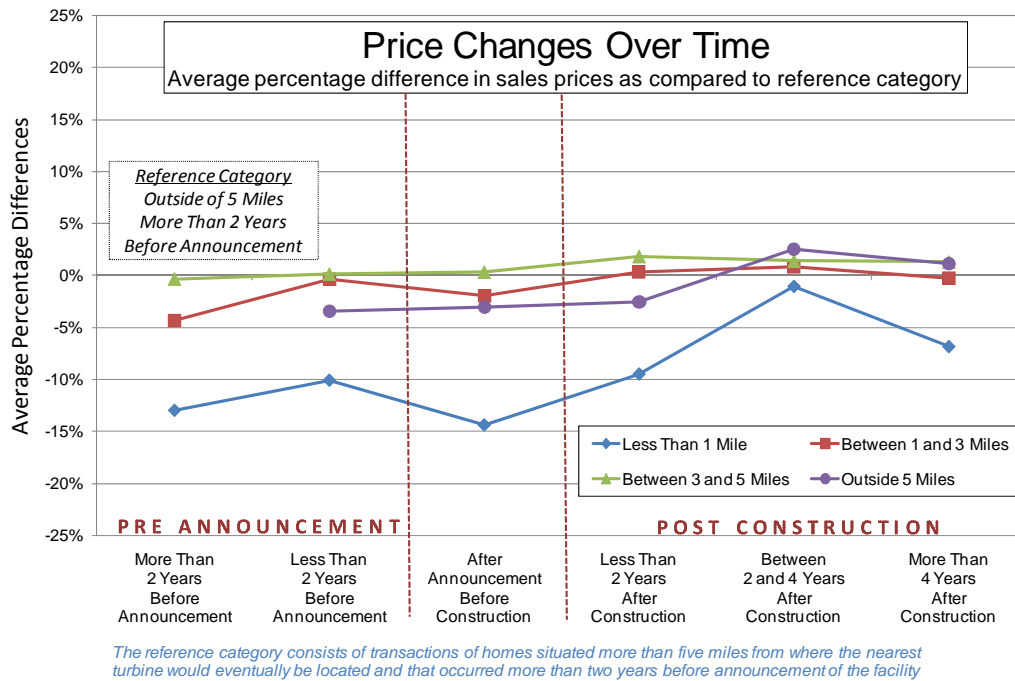
Model Equation Number	7
Dependent Variable	LN_SalePrice96
Number of Cases	7459
Number of Predictors (k)	56
F Statistic	404.5
Adjusted R Squared	0.75

What these results suggest (as shown in Figure 8) is that homes inside of one mile in the sample, on average, were depressed in value (in relation to the reference category) before and after the announcement of the wind facility and up to the point that construction began, but that those values rebounded somewhat after construction commenced.<sup>81</sup> This conclusion also likely explains why a significant and negative effect for homes that sold between 3000 feet and one mile is found in the All Sales Model presented in Section 5.3: homes within this distance range that sold prior to facility construction were depressed in value and most likely drove the results for homes that sold after announcement. Regardless, these results are not suggestive of a pervasive Nuisance Stigma.

<sup>81</sup> As discussed in footnotes 47 (on page 19) and 74 (on page 38), the “announcement date” often refers to the first time the proposed facility appeared in the press. “Awareness” of the project in the community may precede this date, however, and therefore transactions occurring in the period “less than two years before announcement” could conceivably have been influenced by the prospective wind project, but it is considerably less likely that those in the period more than two years before announcement would have been influenced.



**Figure 8: Results from the Temporal Aspects Model**



To explore Nuisance Stigma further, the analysis again turns to the *t*-Test and compares the coefficients for transactions that occurred more than two years before wind facility announcement (during which time the future wind facility is not expected to have any impact on sales prices) to the estimates for the DISTANCE coefficients in the periods that follow. These results are shown in Table 20. Focusing on those transactions inside of one mile, it is found that all coefficients are greater in magnitude than the reference category except during the post-announcement-pre-construction period (which is 1% less and is not statistically significant; *p* value 0.90), indicating, on average, that home values are increasing or staying stable from the pre-announcement reference period onward. These increases, however, are not statistically significant except in the period of two to four years after construction (0.12, *p* value 0.08). With respect to Nuisance Stigma, the more important result is that, relative to homes that sold well before the wind facility was announced, no statistically significant adverse effect is found in any period within a one mile radius of the wind facility. Therefore, the -5% (albeit not statistically significant) average difference that is found in the Base Model, and the -8% (statistically significant) result that is found in the All Sales Model (for homes between 3000 feet and one mile) appear to both be a reflection of depressed home prices that preceded the construction of the relevant wind facilities. If construction of the wind facilities were downwardly influencing the sales prices of these homes, as might be deduced from the Base or All Sales Models alone, a diminution in the inflation adjusted price would be seen as compared to pre-announcement levels. Instead, an increase is seen. As such, no persuasive evidence of a Nuisance Stigma is evident among this sample of transactions.<sup>82</sup>

<sup>82</sup> It should be noted that the numbers of study areas represented for homes situated inside of one mile but in the periods “more than two years before announcement” and “more than four years after construction” are fewer (*n* = 5) than in the other temporal categories (*n* = 8). Further, the “more than two years before announcement – inside of one mile” category is dominated by transactions from one study area (OKCC). For these reasons, there is less

Turning to the coefficient differences for distances greater than one mile in Table 20, again, no statistical evidence of significant adverse impacts on home values is uncovered. Where statistically significant differences are identified, the coefficients are greater than the reference category. These findings corroborate the earlier Area Stigma results, and re-affirm the lack of evidence for such an effect among the sample of residential transactions included in this analysis.

**Table 20: Results from Equality Test of Temporal Aspects Model Coefficients**

	More Than 2 Years Before Announcement	Less Than 2 Years Before Announcement	After Announcement Before Construction	Less Than 2 Years After Construction	Between 2 and 4 Years After Construction	More Than 4 Years After Construction
Less Than 1 Mile	Reference	0.03 (0.45)	-0.01 (-0.13)	0.04 (0.56)	0.12 (1.74)*	0.06 (0.88)
Between 1 and 3 Miles	Reference	0.04 (1.92)*	0.02 (0.86)	0.05 (2.47)**	0.05 (2.27)**	0.04 (1.82)*
Between 3 and 5 Miles	Reference	0.01 (0.37)	0.01 (0.34)	0.02 (0.77)	0.02 (0.78)	0.02 (0.79)
Outside of 5 Miles †	Reference	-0.04 (-0.86)	-0.03 (-0.91)	-0.03 (-0.77)	0.03 (0.81)	0.01 (0.36)

Numbers in parenthesis are t-Test statistics. Significance = \*\*\* 1% level, \*\* 5% level, \* 10% level, <blank> below the 10% level.

† For homes outside of 5 miles, the coefficient differences are equal to the coefficients in the Temporal Aspects Model, and therefore the t-values were produced via the OLS.

## 5.5. Orientation Model

All of the hedonic models presented to this point use a VIEW variable that effectively assumes that the impact of a view of wind turbines on property values will not vary based on the orientation of the home to that view; the impact will be the same whether the view is seen from the side of the home or from the back or front. Other literature, however, has found that the impact of wind projects on property values may be orientation-dependent (Sims et al., 2008). To investigate this possibility further a parameter for orientation is included in the model.

### 5.5.1. Dataset and Model Form

The same dataset is used as in the Base Model, focusing on post-construction transactions ( $n = 4,937$ ). To investigate whether the orientation of a home to the turbines (ORIENTATION) has a marginal impact on residential property values, over and above that of the VIEW impacts alone, the following hedonic model is estimated:<sup>83</sup>

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confidence in these two estimates (-13% and -7% respectively) than for the estimates for other temporal periods inside of one mile. Based on additional sensitivity analysis not included here, it is believed that if they are biased, both of these estimates are likely biased downward. Further, as discussed in footnote 47 on page 19, there is a potential for bias in the “announcement” date in that awareness of a project may precede the date that a project enters the public record (i.e., the “announcement” date used for this analysis). Taken together, these two issues might imply that the curve shown in Figure 8 for “less than one mile” transactions, instead of having a flat and then increasing shape, may have a more of an inverse parabolic (e.g., “U”) shape. This would imply that a relative minimum in sales prices is reached in the period after awareness began of the facility but before construction commenced, and then, following construction, prices recovered to levels similar to those prior to announcement (and awareness). These results would be consistent with previous studies (e.g., Wolsink, 1989; Devine-Wright, 2004) but cannot be confirmed without the presence of more data. Further research on this issue is warranted. In either case, such results would not change the conclusion here of an absence of evidence of a pervasive Nuisance Stigma in the post-construction period.

<sup>83</sup> The various possible orientations of the home to the view of turbines will be, individually and collectively, referred to as “ORIENTATION” in this report.

$$\ln(P) = \beta_0 + \beta_1 N + \sum_s \beta_2 S + \sum_k \beta_3 X + \sum_v \beta_4 \text{VIEW} + \sum_d \beta_5 \text{DISTANCE} + \sum_o \beta_6 \text{ORIENTATION} + \varepsilon \quad (8)$$

where

ORIENTATION is a vector of  $o$  ORIENTATION variables (e.g., SIDE, FRONT, and BACK),  $\beta_6$  is a vector of  $o$  parameter estimates for ORIENTATION variables, and all other components are as defined in equation (1).<sup>84</sup>

The ORIENTATION categories include FRONT, BACK, and SIDE, and are defined as follows:

- SIDE: The orientation of the home to the view of the turbines is from the side.
- FRONT: The orientation of the home to the view of the turbines is from the front.
- BACK: The orientation of the home to the view of the turbines is from the back.

The orientation of the home to the view of the wind facilities was determined in the course of the field visits to each home. If more than one orientation to the turbines best described the home (e.g., back and side, or front, back, and side) they were coded as such (e.g., turbines visible from back and side: SIDE = 1; BACK = 1; FRONT = 0).<sup>85</sup>

Not surprisingly, ORIENTATION is related to VIEW. Table 21 and Table 22 provide frequency and percentage crosstabs of ORIENTATION and VIEW. As shown, those homes with more dramatic views of the turbines generally have more ORIENTATION ratings applied to them. For instance, 25 out of 28 EXTREME VIEW homes have all three ORIENTATION ratings (i.e., FRONT, BACK, and SIDE). Virtually all of the MINOR VIEW homes, on the other hand, have only one ORIENTATION. Further, MINOR VIEW homes have roughly evenly spread orientations to the turbines across the various possible categories of FRONT, BACK, and SIDE. Conversely, a majority of the MODERATE and SUBSTANTIAL VIEW ratings coincide with an ORIENTATION from the back of the house.<sup>86</sup>

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<sup>84</sup> Ideally, one would enter ORIENTATION in the model through an interaction with VIEW. There are two ways that could be accomplished: either with the construction of multiple fixed effects (“dummy”) variables, which capture each sub-category of VIEW and ORIENTATION, or through a semi-continuous interaction variable, which would be created by multiplying the ordered categorical variable VIEW by an ordered categorical variable ORIENTATION. Both interaction scenarios are problematic, the former because it requires increasingly small subsets of data, which create unstable coefficient estimates, and the latter because there are no *a priori* expectations for the ordering of an ordered categorical ORIENTATION variable and therefore none could be created and used for the interaction. As a result, no interaction between the two variables is reported here.

<sup>85</sup> An “Angle” orientation was also possible, which was defined as being between Front and Side or Back and Side. An Angle orientation was also possible in combination with Back or Front (e.g., Back-Angle or Front-Angle). In this latter case, the orientation was coded as one of the two prominent orientations (e.g., Back or Front). An Angle orientation, not in combination with Front or Back, was coded as Side.

<sup>86</sup> The prevalence of BACK orientations for MODERATE and SUBSTANTIAL VIEW homes may be because BACK views might more-frequently be kept without obstruction, relative to SIDE views.

**Table 21: Frequency Crosstab of VIEW and ORIENTATION**

		VIEW				Total
		Minor	Moderate	Substantial	Extreme	
ORIENTATION	Front	217	33	17	27	<b>294</b>
	Back	164	67	24	25	<b>280</b>
	Side	194	17	15	27	<b>253</b>
	Total	<b>561</b>	<b>106</b>	<b>35</b>	<b>28</b>	<b>730</b>

*Note: Total of ORIENTATION does not sum to 730 because multiple orientations are possible for each VIEW.*

**Table 22: Percentage Crosstab of VIEW and ORIENTATION**

		VIEW				Total
		Minor	Moderate	Substantial	Extreme	
ORIENTATION	Front	39%	31%	49%	96%	<b>40%</b>
	Back	29%	63%	69%	89%	<b>38%</b>
	Side	35%	16%	43%	96%	<b>35%</b>

*Note: Percentages are calculated as a portion of the total for each VIEW ratings (e.g., 24 of the 35 SUBSTANTIAL rated homes have a BACK ORIENTATION = 69%). Columns do not sum to 100% because multiple orientations are possible for each VIEW.*

The parameter estimates of interest in this hedonic model are those for ORIENTATION ( $\beta_6$ ) and VIEW ( $\beta_4$ ).  $\beta_6$  represent the marginal impact on home value, over and above that of VIEW alone, of having a particular orientation to the turbines. In the Base Model the VIEW coefficients effectively absorb the effects of ORIENTATION, but in this model they are estimated separately. Because a home’s surrounding environment is typically viewed from the front or back of the house, one would expect that, to the extent that wind facility VIEW impacts property values, that impact would be especially severe for homes that have FRONT or BACK orientations to those turbines. If this were the case, the coefficients for these categories would be negative, while the coefficient for SIDE would be to be close to zero indicating little to no incremental impact from a SIDE ORIENTATION.

### 5.5.2. Analysis of Results

Results for the variables of interest for this hedonic model are shown in Table 23; as with previous models, the full set of results is contained in Appendix H. The model performs well with an adjusted  $R^2$  of 0.77. All study area, spatial adjustment, and home and site characteristics are significant at or above the one percent level, are of the appropriate sign, and are similar in magnitude to the estimates derived from the post-construction Base Model. The coefficients for DISTANCE and VIEW are stable, in sign and magnitude, when compared to the Base Model results, and none of the marginal effects are statistically significant.

The coefficients for the variables of interest ( $\beta_6$ ) do not meet the *a priori* expectations. The estimated effect for SIDE ORIENTATION, instead of being close to zero, is -3% (*p* value 0.36), while BACK and FRONT, instead of being negative and larger, are estimated at 3% (*p* value 0.37) and -1% (*p* value 0.72), respectively. None of these variables are found to be even marginally statistically significant, however, and based on these results, it is concluded that there is no evidence that a home's orientation to a wind facility affects property values in a measurable way. Further, as with previous models, no statistical evidence of a Scenic Vista Stigma is found among this sample of sales transactions.

**Table 23: Results from Orientation Model**

Variables of Interest	Base Model				Orientation Model			
	Coef	SE	p Value	<i>n</i>	Coef	SE	p Value	<i>n</i>
No View	Omitted	Omitted	Omitted	4207	Omitted	Omitted	Omitted	4207
Minor View	-0.01	0.01	0.39	561	-0.01	0.06	0.88	561
Moderate View	0.02	0.03	0.57	106	0.00	0.06	0.96	106
Substantial View	-0.01	0.07	0.92	35	-0.01	0.09	0.85	35
Extreme View	0.02	0.09	0.77	28	0.02	0.17	0.84	28
Inside 3000 Feet	-0.05	0.06	0.31	67	-0.04	0.07	0.46	67
Between 3000 Feet and 1 Mile	-0.05	0.05	0.20	58	-0.05	0.05	0.26	58
Between 1 and 3 Miles	0.00	0.02	0.80	2019	0.00	0.02	0.83	2019
Between 3 and 5 Miles	0.02	0.01	0.26	1923	0.02	0.01	0.26	1923
Outside 5 Miles	Omitted	Omitted	Omitted	870	Omitted	Omitted	Omitted	870
Front Orientation					-0.01	0.06	0.72	294
Back Orientation					0.03	0.06	0.37	280
Side Orientation					-0.03	0.06	0.36	253

"Omitted" = reference category for fixed effects variables. "n" = number of cases in category when category = "1"

**Model Information**

Model Equation Number	1
Dependent Variable	LN_SalePrice96
Number of Cases	4937
Number of Predictors (k)	37
F Statistic	442.8
Adjusted R Squared	0.77

8
LN_SalePrice96
4937
40
410.0
0.77

**5.6. Overlap Model**

The Orientation Model, presented above, investigated, to some degree, how the potential effects of wind turbines might be impacted by how a home is oriented to the surrounding environment. In so doing, this model began to peel back the relationship between VIEW and VISTA, but stopped short of looking at the relationship directly. It would be quite useful, though, to understand the explicit relationship between the VISTA and VIEW variables. In particular, one might expect that views of wind turbines would have a particularly significant impact on residential property values when those views strongly overlap (“OVERLAP”) the prominent scenic vista from a home. To investigate this possibility directly, and, in general, the relationship between VIEW and VISTA, a parameter for OVERLAP is included in the model.

### 5.6.1. Dataset and Model Form

Data on the degree to which the view of wind turbines overlaps with the prominent scenic vista from the home (OVERLAP) were collected in the course of the field visits to each home.<sup>87</sup> The categories for OVERLAP included NONE, BARELY, SOMEWHAT, and STRONGLY, and are described in Table 24:<sup>88</sup>

**Table 24: Definition of OVERLAP Categories**

OVERLAP - NONE	The scenic vista does not contain any view of the turbines.
OVERLAP - BARELY	A small portion (~ 0 - 20%) of the scenic vista is overlapped by the view of turbines, and might contain a view of a few turbines, only a few of which can be seen entirely.
OVERLAP - SOMEWHAT	A moderate portion (~20-50%) of the scenic vista contains turbines, and likely contains a view of more than one turbine, some of which are likely to be seen entirely.
OVERLAP - STRONGLY	A large portion (~50-100%) of the scenic vista contains a view of turbines, many of which likely can be seen entirely.

A crosstab describing the OVERLAP designations and the VIEW categories is shown in Table 25. As would be expected, the more dramatic views of wind turbines, where the turbines occupy more of the panorama, are coincident with the OVERLAP categories of SOMEWHAT or STRONGLY. Nonetheless, STRONGLY are common for all VIEW categories. Similarly, SOMEWHAT is well distributed across the MINOR and MODERATE rated views, while BARELY is concentrated in the MINOR rated views.

The same dataset is used as in the Base Model, focusing on post-construction transactions ( $n = 4,937$ ). To investigate whether the overlap of VIEW and VISTA has a marginal impact on residential property values, over and above that of the VIEW and VISTA impacts alone, the following hedonic model is estimated:<sup>89</sup>

$$\ln(P) = \beta_0 + \beta_1 N + \sum_s \beta_2 S + \sum_k \beta_3 X + \sum_v \beta_4 \text{VIEW} + \sum_d \beta_5 \text{DISTANCE} + \sum_t \beta_6 \text{VISTA} + \sum_p \beta_7 \text{OVERLAP} + \varepsilon \quad (9)$$

where

VIEW is a vector of  $v$  categorical view variables (e.g., MINOR, MODERATE, etc.),  
VISTA is a vector of  $t$  categorical scenic vista variables (e.g., POOR, BELOW-AVERAGE, etc.),  
OVERLAP is a vector of  $p$  categorical overlap variables (e.g., BARELY, SOMEWHAT, etc.),

<sup>87</sup> Scenic vista was rated while taking into account the entire panorama surrounding a home. But, for each home, there usually was a prominent direction that offered a preferred scenic vista. Often, but not always, the home was orientated to enjoy that prominent scenic vista. Overlap is defined as the degree to which the view of the wind facility overlaps with this prominent scenic vista.

<sup>88</sup> "...can be seen entirely" refers to being able to see a turbine from the top of the sweep of its blade tips to below the nacelle of the turbine where the sweep of the tips intersects the tower.

<sup>89</sup> Although VISTA appears in all models, and is usually included in the vector of home and site characteristics represented by X, it is shown separately here so that it can be discussed directly in the text that follows.

$\beta_4$  is a vector of  $v$  parameter estimates for VIEW fixed effects variables as compared to transactions of homes without a view of the turbines,  
 $\beta_6$  is a vector of  $t$  parameter estimates for VISTA fixed effect variables as compared to transactions of homes with an AVERAGE scenic vista,  
 $\beta_7$  is a vector of  $o$  parameter estimates for OVERLAP fixed effect variables as compared to transactions of homes where the view of the turbines had no overlap with the scenic vista, and all other components are as defined in equation (1).

The variables of interest in this model are VIEW, VISTA and OVERLAP, and the coefficients  $\beta_4$ ,  $\beta_6$ , and  $\beta_7$  are therefore the primary focus. Theory would predict that the VISTA coefficients in this model would be roughly similar to those derived in the Base Model, but that the VIEW coefficients may be somewhat more positive as the OVERLAP variables explain a portion of any negative impact that wind projects have on residential sales prices. In that instance, the OVERLAP coefficients would be negative, indicating a decrease in sales price when compared to those homes that experience no overlap between the view of wind turbines and the primary scenic vista.

**Table 25: Frequency Crosstab of OVERLAP and VIEW**

		VIEW					Total
		None	Minor	Moderate	Substantial	Extreme	
OVERLAP	None	4,207	317	3	0	0	4,527
	Barely	0	139	10	1	0	150
	Somewhat	0	81	42	7	2	132
	Strongly	0	24	51	27	26	128
	Total	4,207	561	106	35	28	4,937

### 5.6.2. Analysis of Results

Results for the variables of interest for this hedonic model are shown in Table 26; as with previous models, the full set of results is contained in Appendix H. The model performs well with an adjusted  $R^2$  of 0.77. All study area, spatial adjustment, and home and site characteristics are significant at or above the one percent level, are of the appropriate sign, and are similar in magnitude to the estimates derived from the post-construction Base Model.

As expected from theory, the VISTA parameters are stable across models with no change in coefficient sign, magnitude, or significance. Counter to expectations, however, the VIEW coefficients, on average, decrease in value. MINOR VIEW is now estimated to adversely affect a home's sale price by 3% ( $p$  value 0.10) and is weakly significant, but none of the other VIEW categories are found to be statistically significant. Oddly, the OVERLAP rating of BARELY is found to significantly increase home values by 5% ( $p$  value 0.08), while none of the other OVERLAP ratings are found to have a statistically significant impact.

Taken at face value, these results are counterintuitive. For instance, absent any overlap of view with the scenic vista (NONE), a home with a MINOR view sells for 3% less than a home with no view of the turbines. If, alternatively, a home with a MINOR view BARELY overlaps the prominent scenic vista, it not only enjoys a 2% increase in value over a home with NO VIEW of the turbines but a 5% increase in value over homes with views of the turbines that do not overlap

with the scenic vista. In other words, the sales price increases when views of turbines overlap the prominent scenic vista, at least in the BARELY category. A more likely explanation for these results are that the relatively high correlation (0.68) between the VIEW and OVERLAP parameters is spuriously driving one set of parameters up and the other down. More importantly, when the parameters are combined, they offer a similar result as was found in the Base Model. Therefore, it seems that the degree to which the view of turbines overlaps the scenic vista has a negligible effect on sales prices among the sample of sales transactions analyzed here.<sup>90</sup>

Despite these somewhat peculiar results, other than MINOR, none of the VIEW categories are found to have statistically significant impacts, even after accounting for the degree to which those views overlap the scenic vista. Similarly, none of the OVERLAP variables are simultaneously negative and statistically significant. This implies, once again, that a Scenic Vista Stigma is unlikely to be present in the sample. Additionally, none of the DISTANCE coefficients are statistically significant, and those coefficients remain largely unchanged from the Base Model, reaffirming previous results in which no significant evidence of either an Area or a Nuisance Stigma was found.

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<sup>90</sup> An alternative approach to this model was also considered, one that includes an interaction term between VIEW and VISTA. For this model it is assumed that homes with higher rated scenic vistas might have higher rated views of turbines, and that these views of turbines would decrease the values of the scenic vista. To construct the interaction, VISTA, which can be between one and five (e.g., POOR=1,...PREMIUM=5), was multiplied by VIEW, which can be between zero and four (e.g. NO VIEW=0, MINOR=1,...EXTREME=4). The resulting interaction (VIEW\*VISTA) therefore was between zero and sixteen (there were no PREMIUM VISTA homes with an EXTREME VIEW), with zero representing homes without a view of the turbines, one representing homes with a POOR VISTA and a MINOR VIEW, and sixteen representing homes with either a PREMIUM VISTA and a SUBSTANTIAL VIEW or an ABOVE AVERAGE VISTA and an EXTREME VIEW. The interaction term, when included in the model, was relatively small (-0.013) and weakly significant ( $p$  value 0.10 – not White’s corrected). The VISTA estimates were unchanged and the VIEW parameters were considerably larger and positive. For instance, EXTREME was 2% in the Base Model and 16% in this “interaction” model. Similarly, SUBSTANTIAL was -1% in the Base Model and 13% in this model. Therefore, although the interaction term is negative and weakly significant, the resulting VIEW estimates, to which it would need to be added, fully offset this negative effect. These results support the idea that the degree to which a VIEW overlaps VISTA has a likely negligible effect on sales prices, while also confirming that there is a high correlation between the interaction term and VIEW variables.



**Table 26: Results from Overlap Model**

Variables of Interest	Base Model				Overlap Model			
	Coef	SE	p Value	n	Coef	SE	p Value	n
No View	Omitted	Omitted	Omitted	4,207	Omitted	Omitted	Omitted	4,207
Minor View	-0.01	0.01	0.39	561	-0.03	0.02	0.10	561
Moderate View	0.02	0.03	0.57	106	-0.02	0.04	0.65	106
Substantial View	-0.01	0.07	0.92	35	-0.05	0.09	0.43	35
Extreme View	0.02	0.09	0.77	28	-0.03	0.10	0.73	28
Inside 3000 Feet	-0.05	0.06	0.31	67	-0.05	0.06	0.32	67
Between 3000 Feet and 1 Mile	-0.05	0.05	0.20	58	-0.05	0.05	0.27	58
Between 1 and 3 Miles	0.00	0.02	0.80	2,019	0.00	0.02	0.82	2,019
Between 3 and 5 Miles	0.02	0.01	0.26	1,923	0.02	0.01	0.26	1,923
Outside 5 Miles	Omitted	Omitted	Omitted	870	Omitted	Omitted	Omitted	870
Poor Vista	-0.21	0.02	0.00	310	-0.21	0.02	0.00	310
Below Average Vista	-0.08	0.01	0.00	2,857	-0.08	0.01	0.00	2,857
Average Vista	Omitted	Omitted	Omitted	1,247	Omitted	Omitted	Omitted	1,247
Above Average Vista	0.10	0.02	0.00	448	0.10	0.02	0.00	448
Premium Vista	0.13	0.04	0.00	75	0.13	0.04	0.00	75
View Does Not Overlap Vista					Omitted	Omitted	Omitted	320
View Barely Overlaps Vista					0.05	0.03	0.08	150
View Somewhat Overlaps Vista					0.01	0.03	0.66	132
View Strongly Overlaps Vista					0.05	0.05	0.23	128

"Omitted" = reference category for fixed effects variables. "n" = number of cases in category when category = "1"

**Model Information**

Model Equation Number	1
Dependent Variable	LN_SalePrice96
Number of Cases	4937
Number of Predictors (k)	37
F Statistic	442.8
Adjusted R Squared	0.77

Model Equation Number	9
Dependent Variable	LN_SalePrice96
Number of Cases	4937
Number of Predictors (k)	40
F Statistic	409.7
Adjusted R Squared	0.77

## 6. Repeat Sales Analysis

In general, the Base and Alternative Hedonic Models presented in previous sections come to the same basic conclusion: wind power facilities in this sample have no demonstrable, widespread, sizable, and statistically significant affect on residential property values. These hedonic models contain 29 or more controlling variables (e.g., house and site characteristics) to account for differences in home values across the sample. Although these models perform well and explain nearly 80% of the variation in sales prices among homes in the sample, it is always possible that variables not included in (i.e., “omitted from”) the hedonic models could be correlated with the variables of interest, therefore biasing the results.

A common method used to control for omitted variable bias in the home assessment literature is to estimate a repeat sales model (Palmquist, 1982). This technique focuses on just those homes that have sold on more than one occasion, preferably once before and once after the introduction of a possible disamenity, and investigates whether the price appreciation between these transactions is affected by the presence of that disamenity. In this section a repeat sales analysis is applied to the dataset, investigating in a different way the presence of the three possible property value stigmas associated with wind facilities, and therefore providing an important cross-check to the hedonic model results. The section begins with a brief discussion of the general form of the Repeat Sales Model and a summary of the literature that has employed this approach to investigate environmental disamenities. The dataset and model used in the analysis is then described, followed by a summary of the results from that analysis.

### 6.1. Repeat Sales Models and Environmental Disamenities Literature

Repeat sales models use the annual sales-price appreciation rates of homes as the dependent variable. Because house, home site, and neighborhood characteristics are relatively stable over time for any individual home, many of those characteristics need not be included in the repeat sales model, thereby increasing the degrees of freedom and allowing sample size requirements to be significantly lower and coefficient estimates to be more efficient (Crone and Voith, 1992). A repeat sales analysis is not necessarily preferred over a traditional hedonic model, but is rather an alternative analysis approach that can be used to test the robustness of the earlier results (for further discussion see Jackson, 2003). The repeat sales model takes the basic form:

Annual Appreciation Rate (AAR) =  $f$ (TYPE OF HOUSE, OTHER FACTORS)

where

TYPE OF HOUSE provides an indication of the segment of the market in which the house is situated (e.g., high end vs. low end), and

OTHER FACTORS include, but are not limited to, changes to the environment (e.g., proximity to a disamenity).

The dependent variable is the adjusted annual appreciation rate and is defined as follows:

$$\text{AAR} = \exp \left[ \frac{\ln(P_1 / P_2)}{t_1 - t_2} \right] - 1 \quad (10)$$

where

$P_1$  is the adjusted sales price at the first sale (in 1996 dollars),  
 $P_2$  is the adjusted sales price at the second sale (in 1996 dollars),  
 $t_1$  is the date of the first sale,  
 $t_2$  is the date of the second sale, and  
 $(t_1 - t_2)$  is determined by calculating the number of days that separate the sale dates and dividing by 365.

As with the hedonic regression model, the usefulness of the repeat sales model is well established in the literature when investigating possible disamenities. For example, a repeat sales analysis was used to estimate spatial and temporal sales price effects from incinerators by Kiel and McClain (1995), who found that appreciation rates, on average, are not sensitive to distance from the facility during the construction phase but are during the operation phase. Similarly, McCluskey and Rausser (2003) used a repeat sales model to investigate effects surrounding a hazardous waste site. They found that appreciation rates are not sensitive to the home's distance from the disamenity before that disamenity is identified by the EPA as hazardous, but that home values are impacted by distance after the EPA's identification is made.

## 6.2. Dataset

The 7,459 residential sales transactions in the dataset contain a total of 1,253 transactions that involve homes that sold on more than one occasion (i.e., a "pair" of sales of the same home). For the purposes of this analysis, however, the key sample consists of homes that sold once before the announcement of the wind facility, and that subsequently sold again after the construction of that facility. Therefore any homes that sold twice in either the pre-announcement or post-construction periods were not used in the repeat sales sample.<sup>91</sup> These were excluded because either they occurred before the effect would be present (for pre-announcement pairs) or after (for post-announcement pairs). This left a total of 368 pairs for the analysis, which was subsequently reduced to 354 usable pairs.<sup>92</sup>

The mean AAR for the sample is 1.0% per year, with a low of -10.5% and a high of 13.4%. Table 27 summarizes some of the characteristics of the homes used in the repeat sales model. The average house in the sample has 1,580 square feet of above-ground finished living area, sits on a parcel of 0.67 acres, and originally sold for \$70,483 (real 1996 dollars). When it sold a second time, the average home in the sample was located 2.96 miles from the nearest wind turbine (14 homes were within one mile, 199 between one and three miles, 116 between three and five miles, and 25 outside of five miles). Of the 354 homes, 14% ( $n = 49$ ) had some view of the facility (35 were rated MINOR, five MODERATE, and nine either SUBSTANTIAL or EXTREME). Because of the restriction to those homes that experienced repeat sales, the sample is relatively small for those homes in close proximity to and with dramatic views of wind facilities.

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<sup>91</sup> 752 pairs occurred after construction began, whereas 133 pairs occurred before announcement.

<sup>92</sup> Of the 368 pairs, 14 were found to have an AAR that was either significantly above or below the mean for the sample (mean +/- 2 standard deviations). These pairs were considered highly likely to be associated with homes that were either renovated or left to deteriorate between sales, and therefore were removed from the repeat sales model dataset. Only two of these 14 homes had views of the wind turbines, both of which were MINOR. All 14 of the homes were situated either between one and three miles from the nearest turbine ( $n = 8$ ) or between three and five miles away ( $n = 6$ ).

**Table 27: List of Variables Included in the Repeat Sales Model**

Variable Name	Description	Type	Sign	Freq.	Mean	Std. Dev.	Min.	Max.
SalePrice96_Pre	The Sale Price (adjusted for inflation into 1996 dollars) of the home as of the first time it had sold	C	+	354	\$ 70,483	\$ 37,798	\$ 13,411	\$ 291,499
SalePrice96_Pre_Sqr	SalePrice96_Pre Squared (shown in millions)	C	-	354	\$ 6,393	\$ 8,258	\$ 180	\$ 84,972
Acres	Number of Acres that sold with the residence	C	+	354	0.67	1.34	0.07	10.96
Sqft_1000	Number of square feet of finished above ground living area (in 1000s)	C	+	354	1.58	0.56	0.59	4.06
No View	If the home had no view of the turbines when it sold for the second time (Yes = 1, No = 0)	Omitted	n/a	305	0.86	0.35	0	1
Minor View	If the home had a Minor View of the turbines when it sold for the second time (Yes = 1, No = 0)	OC	-	35	0.10	0.30	0	1
Moderate View	If the home had a Moderate View of the turbines when it sold for the second time (Yes = 1, No = 0)	OC	-	5	0.01	0.12	0	1
Substantial/Extreme View	If the home had a Substantial or Extreme View of the turbines when it sold for the second time (Yes = 1, No = 0)	OC	-	9	0.03	0.12	0	1
Less than 1 Mile	If the home was within 1 mile (5280 feet) of the turbines when it sold for the second time (Yes = 1, No = 0)	OC	-	14	0.02	0.13	0	1
Between 1 and 3 Miles	If the home was between 1 and 3 miles of the turbines when it sold for the second time (Yes = 1, No = 0)	OC	-	199	0.56	0.50	0	1
Between 3 and 5 Miles	If the home was between 3 and 5 miles of the turbines when it sold for the second time (Yes = 1, No = 0)	OC	-	116	0.33	0.47	0	1
Outside 5 Miles	If the home was outside 5 miles of the turbines when it sold for the second time (Yes = 1, No = 0)	Omitted	n/a	25	0.07	0.26	0	1

"C" Continuous, "OC" Ordered Categorical (1 = yes, 0 = no) values are interpreted in relation to the "Omitted" category. This table does not include the study area fixed effects variables that are included in the model (e.g., WAOR, TXHC, NYMC). The reference case for these variables is the WAOR study area.

### 6.3. Model Form

To investigate the presence of Area, Scenic Vista, and Nuisance Stigmas, the adjusted annual appreciation rate (AAR) is calculated for the 354 sales pairs in the manner described in equation (10), using inflation adjusted sales prices. The following model is then estimated:

$$AAR = \beta_0 + \sum_s \beta_1 S + \sum_k \beta_2 X + \sum_v \beta_3 VIEW + \sum_d \beta_4 DISTANCE + \varepsilon \quad (11)$$

where

AAR represents the inflation-adjusted Annual Appreciation Rate for repeat sales,

S is the vector of  $s$  Study Area fixed effects variables (e.g., WAOR, OKCC, etc.),

X is a vector of  $k$  home, site and sale characteristics (e.g., acres, square feet, original sales price),

VIEW is a vector of  $v$  categorical view variables (e.g., MINOR, MODERATE, etc.),

DISTANCE is a vector of  $d$  categorical distance variables (e.g., less than one mile, between one and three miles, etc.),

$\beta_0$  is the constant or intercept across the full sample,

$\beta_1$  is a vector of  $s$  parameter estimates for the study area fixed effects as compared to sales that occurred in the WAOR study area,

$\beta_2$  is a vector of  $k$  parameter estimates for the home, site, and sale characteristics,

$\beta_3$  is a vector of  $v$  parameter estimates for the VIEW variables as compared to transactions of homes with no view of the turbines,

$\beta_4$  is a vector of  $d$  parameter estimates for the DISTANCE variables as compared to transactions of homes outside of five miles, and

$\varepsilon$  is a random disturbance term.

Effectively, this model seeks to identify reasons that AARs vary among those sales pairs in the sample. Reasons for such differences in AARs might include variations in home and site characteristics, the study area in which the sale occurs, or the degree to which the home is in proximity to or has a dramatic view of a wind facility. As such, the model as shown by equation (11) has three primary groups of parameters: variables of interest; home, site, and sale characteristics; and study area fixed effects.

The variables of interest are VIEW and DISTANCE, and the coefficients  $\beta_3$  and  $\beta_4$  are therefore the primary focus of this analysis. Because of the small numbers of homes in the sample situated inside of 3000 feet and between 3000 feet and one mile, they are collapsed into a single category (inside one mile). For the same reason, homes with SUBSTANTIAL or EXTREME VIEWS are collapsed into a single category (SUBSTANTIAL/EXTREME). In this model, therefore, the influence on appreciation rates of the following variables of interest is estimated: MINOR, MODERATE, and SUBSTANTIAL/EXTREME VIEWS, and less than one mile, between one and three mile, and between three and five mile DISTANCES. For the VIEW fixed-effects variables, the reference category is NO VIEW; for DISTANCE, it is homes outside of five miles. As with previous models, if effects exist, it is expected that all of the coefficients would be negative and monotonically ordered.

The number of home, site, and sale characteristics included in a repeat sales model is typically substantially lower than in a hedonic model. This is to be expected because, as discussed earlier, the repeat sales model explores variations in AARs for sales pairs from individual homes, and home and site characteristics are relatively stable over time for any individual home. Nonetheless, various characteristics have been found by others (e.g., Kiel and McClain, 1995; McCluskey and Rausser, 2003) to affect appreciation rates. For the purposes of the Repeat Sales Model, these include the number of square feet of living space (SQFT\_1000), the number of acres (ACRES), the inflation-adjusted price of the home at the first sale (SalePrice96\_Pre), and that sales price squared (SalePrice96\_Pre\_Sqr). Of those characteristics, the SQFT\_1000 and ACRES coefficients are expected to be positive indicating that, all else being equal, an increase in living area and lot size increases the relative appreciation rate. Conversely, it is expected that the combined estimated effect of the initial sales prices (SalePrice96\_Pre and SalePrice96\_Pre\_Sqr) will trend downward, implying that as the initial sales price of the house increases the appreciation rate decreases. These expectations are in line with the previous literature (Kiel and McClain, 1995; McCluskey and Rausser, 2003).

Finally, the study-area fixed effects variables ( $\beta_l$ ) are included in this model to account for differences in inflation adjusted appreciation rates that may exist across study areas (e.g., WAOR, TXHC, NYMC). The WAOR study area is the reference category, and all study-area coefficients therefore represent the marginal change in AARs compared to WAOR (the intercept represents the marginal change in AAR for WAOR by itself). These study area parameters provide a unique look into Area Stigma effects. Recall that the appreciation rates used in this model are adjusted for inflation by using an inflation index from the nearby municipal statistical area (MSA). These MSAs are sometimes quite far away (as much as 20 miles) and therefore would be unaffected by the wind facility. As such, any variation in the study area parameters (and the intercept) would be the result of local influences not otherwise captured in the inflation

adjustment, and represent another test for Area Stigma; if effects exist, it is expected that the  $\beta_0$  and  $\beta_1$  coefficients will be negative.

As with the hedonic models presented earlier, the assumptions of homoskedasticity, absence of spatial autocorrelation, reasonably little multicollinearity, and appropriate controls for outliers are addressed as described in the associated footnote and in Appendix G.<sup>93</sup>

#### 6.4. Analysis of Results

The results from the Repeat Sales Model are presented in Table 28. The model performs relatively poorly overall, with an Adjusted  $R^2$  of just 0.19 (and an  $F$ -test statistic of 5.2). Other similar analyses in the literature have produced higher performance statistics but have done so with samples that are considerably larger or more homogenous than ours.<sup>94</sup> The low  $R^2$  found here should not be cause for undue concern, however, given the relatively small sample spread across ten different study areas. Moreover, many of the home and site characteristics are found to be statistically significant, and of the appropriate sign. The coefficient for the adjusted initial sales price (SalePrice96\_Pre), for example, is statistically significant, small, and negative (-0.000001,  $p$  value 0.00), while the coefficient for the adjusted initial sales price squared (SalePrice96\_Pre\_Sqr) is also statistically significant and considerably smaller (<0.000000,  $p$  value 0.00). These results imply, consistent with the prior literature, that for those homes in the sample, an increase in initial adjusted sales price decreases the average percentage appreciation rate. ACRES (0.002,  $p$  value 0.10) and SQFT\_1000 (0.02,  $p$  value 0.00) are both positive, as expected, and statistically significant.

Of particular interest are the intercept term and the associated study-area fixed effect coefficients, and what they collectively say about Area Stigma. The coefficient for the intercept ( $\beta_0$ ) is 0.005 ( $p$  value 0.81), which is both extremely small and not statistically significant. Likewise, the study-area fixed effects are all relatively small (less than 0.03 in absolute terms) and none are statistically significant. As discussed above, if a pervasive Area Stigma existed, it would be expected to be represented in these coefficients. Because all are small and statistically insignificant, it can again be concluded that there is no persuasive evidence of an Area Stigma among this sample of home transactions.

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<sup>93</sup> All results are produced using White's corrected standard errors to control for heteroskedasticity. Spatial autocorrelation, with this small sample, is impossible to control. Because of the small sample, an even smaller number of neighboring sales exist, which are required to construct the spatial matrix. As such, spatial autocorrelation is not addressed in the repeat sales model. As with the hedonic models, some multicollinearity might exist, but that multicollinearity is unlikely to be correlated with the variables of interest. Outliers are investigated and dealt with as discussed in footnote 91 on page 56.

<sup>94</sup> McCluskey and Rausser (2003) had a sample of over 30,000 repeat sales and had an  $F$ -test statistic of 105; Kiel and McClain (1995) produced an  $R^2$  that ranged from 0.40 to 0.63 with samples ranging from 53 to 145, but all sales took place in North Andover, MA.

**Table 28: Results from Repeat Sales Model**

	Coef.	SE	p Value	n
Intercept	0.005	0.02	0.81	354
WAOR	Omitted	Omitted	Omitted	6
TXHC	-0.01	0.02	0.63	57
OKCC	0.03	0.02	0.11	102
IABV	0.02	0.02	0.14	59
ILLC	-0.01	0.02	0.38	18
WIKCDC	0.02	0.03	0.50	8
PASC	-0.01	0.02	0.67	32
PAWC	0.02	0.02	0.16	35
NYMCOC	0.02	0.02	0.23	24
NYMC	0.03	0.02	0.13	13
SalePrice96 Pre	-0.000001	0.0000002	0.00	354
SalePrice96 Pre Sqr	0.0000000	0.0000000	0.00	354
Acres	0.002	0.001	0.10	354
Sqft 1000	0.02	0.01	0.00	354
No View	Omitted	Omitted	Omitted	305
Minor View	-0.02	0.01	0.02	35
Moderate View	0.03	0.03	0.29	5
Substantial/Extreme View	-0.02	0.01	0.09	9
Less than 1 Mile	0.03	0.01	0.01	14
Between 1 and 3 Miles	0.01	0.01	0.59	199
Between 3 and 5 Miles	0.01	0.01	0.53	116
Outside 5 Miles	Omitted	Omitted	Omitted	25

"Omitted" = reference category for fixed effects variables

"n" indicates number of cases in category when category = "1"

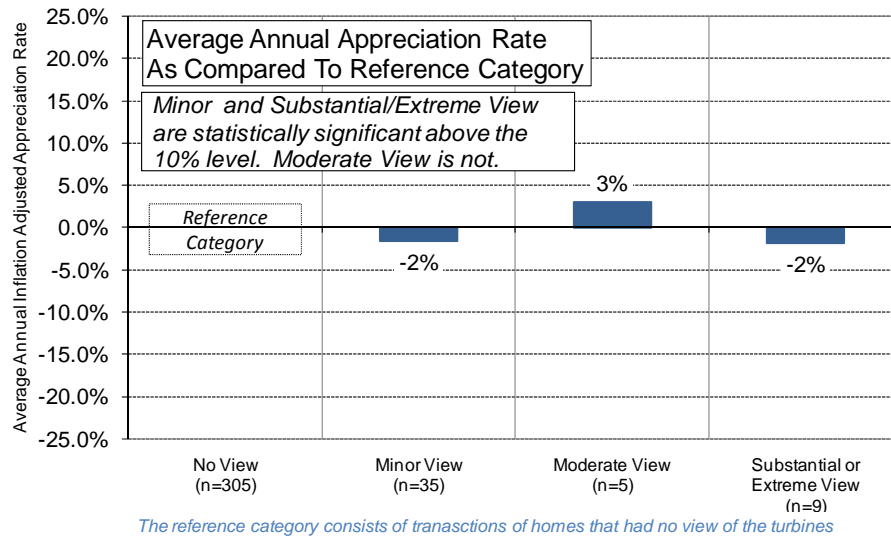
**Model Information**

Model Equation Number	11
Dependent Variable	SalePrice96 AAR
Number of Cases	354
Number of Predictors (k)	19
F Statistic	5.2
Adjusted R2	0.19

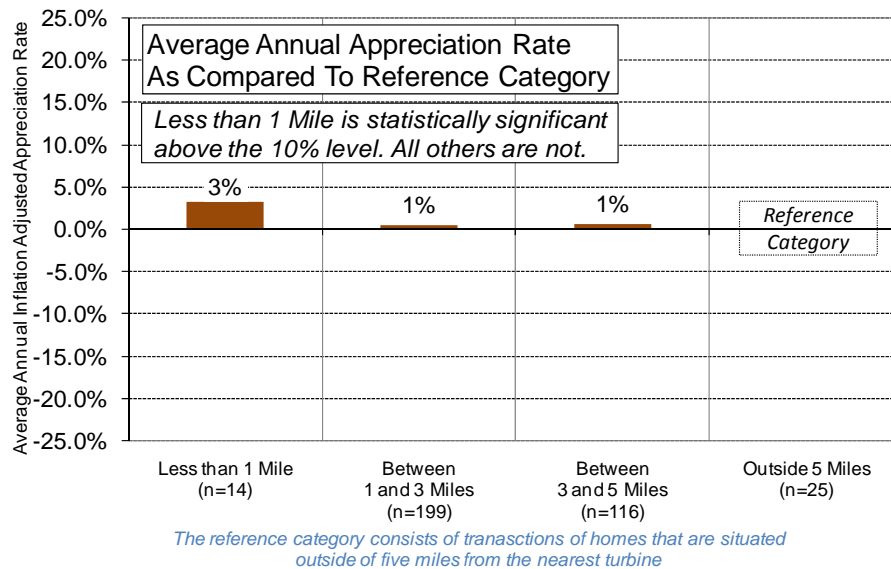
Turning to the variables of interest, mixed results (see Figure 9 and Figure 10) are found. For homes with MINOR or SUBSTANTIAL/EXTREME VIEWS, despite small sample sizes, appreciation rates after adjusting for inflation are found to decrease by roughly 2% annually ( $p$  values of 0.02 and 0.09, respectively) compared to homes with NO VIEW. Though these findings initially seem to suggest the presence of Scenic Vista Stigma, the coefficients are not monotonically ordered, counter to what one might expect: homes with a MODERATE rated view appreciated on average 3% annually ( $p$  value 0.29) compared to homes with NO VIEW. Adding to the suspicion of these VIEW results, the DISTANCE coefficient for homes situated inside of one mile, where eight out of the nine SUBSTANTIAL/EXTREME rated homes are located, is positive and statistically significant (0.03,  $p$  value 0.01). If interpreted literally, these results suggest that a home inside of one mile with a SUBSTANTIAL/EXTREME rated view would experience a decrease in annual appreciation of 2% compared to homes with no views of turbines, but simultaneously would experience an increase of 3% in appreciation compared to homes outside of five miles. Therefore, when compared to those homes outside of five miles and with no view of the wind facilities, these homes would experience an overall increase in AAR by 1%. These results are counterintuitive and are likely driven by the small number of sales pairs

that are located within one mile of the wind turbines and experience a dramatic view of those turbines.

**Figure 9: Repeat Sales Model Results for VIEW**



**Figure 10: Repeat Sales Model Results for DISTANCE**



Regardless of the reason for this result, again no persuasive evidence of consistent and widespread adverse effects is found from the presence of the wind facilities in the sample, reinforcing the findings from the previous hedonic analysis. Specifically, there is no evidence that an Area Stigma exists in that homes outside of one mile and inside of five miles do not appreciate differently than homes farther away. Similarly, there is no evidence of a Nuisance Stigma. Appreciation rates for homes inside of one mile are not adversely affected; in fact, significantly higher appreciation rates are found for these homes than for those homes located outside of five miles from the nearest wind facility. Finally, though some evidence is found that a Scenic Vista Stigma may exist in the sample of repeat sales, it is weak, fairly small, and



somewhat counter-intuitive. This result is likely driven by the small number of sales pairs that are located within one mile of the wind turbines and that experience a dramatic view of those turbines.

## 7. Sales Volume Analysis

The analysis findings to this point suggest that, among the sample of sales transactions analyzed in this report, wind facilities have had no widespread and statistically identifiable impact on residential property values. A related concern that has not yet been addressed is that of sales volume: does the presence of wind facilities either increase or decrease the rate of home sales transactions? On the one hand, a decrease in sales volumes might be expected. This might occur if homeowners expect that their property values will be impacted by the presence of the wind facility, and therefore simply choose not to sell their homes as a result, or if they try to sell but are not easily able to find willing buyers. Alternatively, an increase in sales volume might be expected if homeowners that are located near to or have a dominating view of wind turbines are uncomfortable with the presence of those turbines. Though those homes may sell at a market value that is not impacted by the presence of the wind facilities, self-selection may lead to accelerated transaction volumes shortly after facility announcement or construction as homeowners who view the turbines unfavorably sell their homes to individuals who are not so stigmatized. To address the question of whether and how sales volumes are impacted by nearby wind facilities, sales volumes are analyzed for those homes located at various distances from the wind facilities in the sample, during different facility development periods.

### 7.1. Dataset

To investigate whether sales volumes are affected by the presence of wind facilities two sets of data are assembled: (1) the number of homes available to sell annually within each study area, and (2) the number of homes that actually did sell annually in those areas. Homes potentially “available to sell” are defined as all single family residences within five miles of the nearest turbine that are located on a parcel of land less than 25 acres in size, that have only one residential structure, and that had a market value (for land and improvements) above \$10,000.<sup>95</sup> Homes that “did sell” are defined as every valid sale of a single family residence within five miles of the nearest turbine that are located on a parcel of land less than 25 acres in size, that have only one residential structure, and that sold for more than \$10,000.

The sales data used for this analysis are slightly different from those used in the hedonic analysis reported earlier. As mentioned in Section 3.3, a number of study areas were randomly sampled to limit the transactions outside of 3 miles if the total number of transactions were to exceed that which could efficiently be visited in the field ( $n \sim 1,250$ ). For the sales volume analysis, however, field data collection was not required, and all relevant transactions could therefore be used. Secondly, two study areas did not provide the data necessary for the sales volume analysis (WAOR and OKCC), and are therefore excluded from the sample. Finally, data for some homes that were “available to sell” were not complete, and rather than including only a small selection of these homes, these subsets of data were simply excluded from the analysis. These excluded homes include those located outside of five miles of the nearest wind turbine, and those available to sell or that did sell more than three years before wind facility announcement.<sup>96</sup> The resulting

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<sup>95</sup> “Market value” is the estimated price at which a home would sell as of a given point in time.

<sup>96</sup> For instance, some providers supplied sales data out to ten miles, but only provided homes available to sell out to five miles. As well, data on homes that did sell were not consistently available for periods many years before announcement.

dataset spans the period starting three years prior to facility announcement and ending four years after construction. All homes in this dataset are situated inside of five miles, and each is located in one of the eight represented study areas.<sup>97</sup>

The final set of homes potentially “available to sell” and that actually “did sell” are then segmented into three distance categories: inside of one mile, between one and three miles, and between three and five miles. For each of these three distance categories, in each of the eight study areas, and for each of the three years prior to announcement, the period between announcement and construction, and each of the four years following construction, the number of homes that sold as a percentage of those available to sell is calculated.<sup>98</sup> This results in a total of 24 separate sales volume calculations in each study area, for a total of 192 calculations across all study areas. Finally, these sales volumes are averaged across all study areas into four development period categories: less than three years before announcement, after announcement but before construction, less than two years after construction, and between two and four years after construction.<sup>99</sup> The resulting average annual sales volumes, by distance band and development period, are shown in Table 29 and Figure 11.

**Table 29: Sales Volumes by PERIOD and DISTANCE**

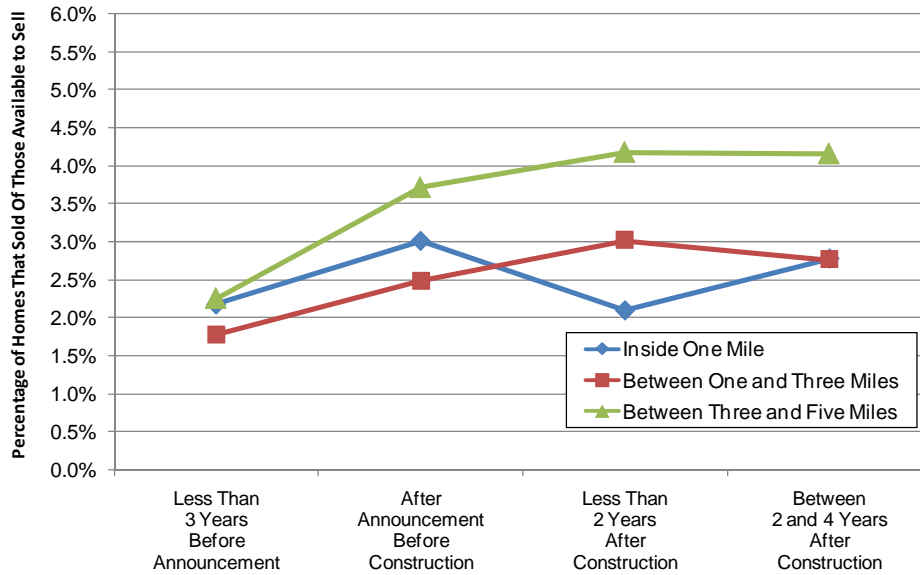
	<b>Inside 1 Mile</b>	<b>Between 1 and 3 Miles</b>	<b>Between 3 and 5 Miles</b>
<b>Less Than 3 Years Before Announcement</b>	2.2%	1.8%	2.3%
<b>After Announcement Before Construction</b>	3.0%	2.5%	3.7%
<b>Less Than 2 Years After Construction</b>	2.1%	3.0%	4.2%
<b>Between 2 and 4 Years After Construction</b>	2.8%	2.8%	4.2%

<sup>97</sup> The number of homes “available to sell” is constructed for each year after 1996 based on the year the homes in each study area were built. For many homes in the sample, the year built occurred more than three years before wind facility announcement, and therefore those homes are “available to sell” in all subsequent periods. For some homes, however, the home was built during the wind facility development process, and therefore becomes “available” some time after the first period of interest. For those homes, the build year is matched to the development dates so that it becomes “available” during the appropriate period. For this reason, the number of homes “available to sell” increases in later periods.

<sup>98</sup> For the period after announcement and before construction, which in all study areas was not exactly 12 months, the sales volume numbers are adjusted so that they corresponded to an average over a 12 month period.

<sup>99</sup> These temporal groupings are slightly different from those used in the hedonic Temporal Aspects Model. Namely, the period before announcement is not divided into two parts – more than two years before announcement and less than two years before announcement – but rather only one – less than three years before announcement. This simplification is made to allow each of the interaction categories to have enough data to be meaningful.

**Figure 11: Sales Volumes by PERIOD and DISTANCE**



## 7.2. Model Form

To investigate whether the rate of sales transactions is measurably affected by the wind facilities, the various resulting sales volumes shown above in Table 29 and Figure 11 are compared using a *t*-Test, as follows:

$$t = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (12)$$

where

$\bar{x}_1$  and  $\bar{x}_2$  are the mean sales volumes from the two categories being compared,

$s_1^2$  and  $s_2^2$  are variances of the sales volumes from the two categories being compared, and

$n_1$  and  $n_2$  are numbers of representative volumes in the two categories.<sup>100</sup>

The degrees of freedom used to calculate the *p*-value of the *t* statistic equals the lower of ( $n_1 - 1$ ) or ( $n_2 - 1$ ).

Three sets of *t*-Tests are conducted. First, to test whether sales volumes have changed with time and are correlated with wind facility construction, the volumes for each DISTANCE group in later periods ( $x_1$ ) are compared to the volume in that same group in the pre-announcement period ( $x_2$ ). Second, to test whether sales volumes are impacted by distance to the nearest wind turbine, the volumes for each PERIOD group at distances closer to the turbines ( $x_1$ ) are compared to the volume in that same group in the three to five mile distance band ( $x_2$ ). Finally, for reasons that will become obvious later, the sales volumes for each PERIOD group at distances within one

<sup>100</sup> The number of representative volumes could differ between the two categories. For instance, the “less than three years before announcement” category represents three years – and therefore three volumes – for each study area for each distance band, while the “less than two years after construction” category represents two years – and therefore two volumes – for each study area for each distance band.

mile and outside of three miles of the turbines ( $x_1$ ) are compared to the sales volume in that same group in the one to three mile distance band ( $x_2$ ). These three tests help to evaluate whether sales volumes are significantly different after wind facilities are announced and constructed, and whether sales volumes near the turbines are affected differently than for those homes located farther away.<sup>101</sup>

### 7.3. Analysis of Results

Table 29 and Figure 11 above show the sales volumes in each PERIOD and DISTANCE category, and can be interpreted as the percentage of homes that are available to sell that did sell in each category, on an annual average basis. The sales volume between one and three miles and before facility announcement is the lowest, at 1.8%, whereas the sales volumes for homes located between three and five miles in both periods following construction are the highest, at 4.2%.

The difference between these two sales volumes can be explained, in part, by two distinct trends that are immediately noticeable from the data presented in Figure 11. First, sales volumes in all periods are highest for those homes located in the three to five mile distance band. Second, sales volumes at virtually all distances are higher after wind facility announcement than they were before announcement.<sup>102</sup>

To test whether these apparent trends are borne out statistically the three sets of  $t$ -Tests described earlier are performed, the results of which are shown in Table 30, Table 31, and Table 32. In each table, the difference between the subject volume ( $x_1$ ) and the reference volume ( $x_2$ ) is listed first, followed by the  $t$  statistic, and whether the statistic is significant at or above the 90% level (“\*”).

Table 30 shows that mean sales volumes in the post-announcement periods are consistently greater than those in the pre-announcement period, and that those differences are statistically significant in four out of the nine categories. For example, the post-construction sales volumes for homes in the three to five mile distance band in the period less than two years after construction (4.2%) and between three and four years after construction (4.2%) are significantly greater than the pre-announcement volume of 2.3% (1.9%,  $t = 2.40$ ; 1.9%,  $t = 2.31$ ). Similarly, the post-construction sales volumes between one and three miles are significantly greater than the pre-announcement volume. These statistically significant differences, it should be noted, could be as much related to the low reference volume (i.e., sales volume in the period less than

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<sup>101</sup> An alternative method to this model would be to pool the homes that “did sell” with the homes “available to sell” and construct a Discrete Choice Model where the dependent variable is zero (for “no sale”) or one (for “sale”) and the independent variables would include various home characteristics and the categorical distance variables. This would allow one to estimate the probability that a home sells dependent on distance from the wind facility. Because home characteristics data for the homes “available to sell,” was not systematically collected it was not possible to apply this method to the dataset.

<sup>102</sup> It is not entirely clear why these trends exist. Volumes may be influenced upward in areas farther from the wind turbines, where homes, in general, might be more densely sited and homogenous, both of which might be correlated with greater home sales transactions. The converse might be true in more rural areas, nearer the wind turbines, where homes may be more unique or homeowners less prone to move. The increasing sales volumes seen in periods following construction, across all distance bands, may be driven by the housing bubble, when more transactions were occurring in general.

three years before announcement), as they are to the sales volumes to which the reference category is compared. Finally, when comparing post-construction volumes inside of a mile, none are statistically different than the 2.2% pre-announcement level.

**Table 30: Equality Test of Sales Volumes between PERIODS**

	<b>Inside 1 Mile</b>	<b>Between 1 and 3 Miles</b>	<b>Between 3 and 5 Miles</b>
<b>Less Than 3 Years Before Announcement</b>	Reference	Reference	Reference
<b>After Announcement Before Construction</b>	0.8% (0.72)	0.7% (0.99)	1.5% (1.49)
<b>Less Than 2 Years After Construction</b>	-0.1% (-0.09)	1.2% (2.45) *	1.9% (2.4) *
<b>Between 2 and 4 Years After Construction</b>	0.6% (0.54)	1% (2.24) *	1.9% (2.31) *

*Numbers in parenthesis represent t-Test statistics. "\*" = significantly different at or below the 10% level*

Turning to sales volumes in the same development period but between the different distance bands, consistent but less statistically significant results are uncovered (see Table 31). Although all sales volumes inside of three miles, for each period, are less than their peers outside of three miles, those differences are statistically significant in only two out of eight instances. Potentially more important, when one compares the sales volumes inside of one mile to those between one and three miles (see Table 32), small differences are found, none of which are statistically significant. In fact, on average, the sales volumes for homes inside of one mile are greater or equal to the volumes of those homes located between one and three miles in two of the three post-announcement periods. Finally, it should be noted that the volumes for the inside one mile band, in the period immediately following construction, are less than those in the one to three mile band in the same period. Although not statistically significant, this difference might imply an initial slowing of sales activity that, in later periods, returns to more normal levels. This possibility is worth investigating further and is therefore recommended for future research.

**Table 31: Equality Test of Volumes between DISTANCES using 3-5 Mile Reference**

	<b>Inside 1 Mile</b>	<b>Between 1 and 3 Miles</b>	<b>Between 3 and 5 Miles</b>
<b>Less Than 3 Years Before Announcement</b>	-0.1% (-0.09)	-0.5% (-0.88)	Reference
<b>After Announcement Before Construction</b>	-0.7% (-0.56)	-1.2% (-1.13)	Reference
<b>Less Than 2 Years After Construction</b>	-2.1% (-2.41) *	-1.2% (-1.48)	Reference
<b>Between 2 and 4 Years After Construction</b>	-1.4% (-1.27)	-1.4% (-1.82) *	Reference

*Numbers in parenthesis represent t-Test statistics. "\*" = significantly different at or below the 10% level*

**Table 32: Equality Test of Sales Volumes between DISTANCES using 1-3 Mile Reference**

	<b>Inside 1 Mile</b>	<b>Between 1 and 3 Miles</b>	<b>Between 3 and 5 Miles</b>
<b>Less Than 3 Years Before Announcement</b>	0.4% (0.49)	Reference	0.5% (0.88)
<b>After Announcement Before Construction</b>	0.5% (0.47)	Reference	1.2% (1.13)
<b>Less Than 2 Years After Construction</b>	-0.9% (-1.38)	Reference	1.2% (1.48)
<b>Between 2 and 4 Years After Construction</b>	0% (0.01)	Reference	1.4% (1.82) *

*Numbers in parenthesis represent t-Test statistics. "\*" = significantly different at or below the 10% level*

Taken together, these results suggest that sales volumes are not conclusively affected by the announcement and presence of the wind facilities analyzed in this report. At least among this sample, sales volumes increased in all distance bands after the announcement and construction of the wind facilities. If this result was driven by the presence of the wind facilities, however, one would expect that such impacts would be particularly severe for those homes in close proximity to wind facilities. In other words, sales volumes would be the most affected inside of one mile, where views of the turbines are more frequent and where other potential nuisances are more noticeable than in areas farther away. This is not borne out in the data - no statistically significant differences are found for sales volumes inside of one mile as compared to those between one and three miles, and sales volumes outside of three miles are higher still. Therefore, on the whole, this analysis is unable to find persuasive evidence that wind facilities have a widespread and identifiable impact on overall residential sales volumes. It is again concluded that neither Area nor Nuisance Stigma are in evidence in this analysis.

## 8. Wind Projects and Property Values: Summary of Key Results

This report has extensively investigated the potential impacts of wind power facilities on the value (i.e., sales prices) of residential properties that are in proximity to and/or that have a view of those wind facilities. In so doing, three different potential impacts of wind projects on property values have been identified and analyzed: Area Stigma, Scenic Vista Stigma, and Nuisance Stigma. To assess these potential impacts, a primary (Base) hedonic model has been applied, seven alternative hedonic models have been explored, a repeat sales analysis has been conducted, and possible impacts on sales volumes have been evaluated. Table 33 outlines the resulting ten tests conducted in this report, identifies which of the three potential stigmas those tests were designed to investigate, and summarizes the results of those investigations. This section synthesizes these key results, organized around the three potential stigmas.

**Table 33: Impact of Wind Projects on Property Values: Summary of Key Results**

Statistical Model	<u>Is there statistical evidence of:</u>			Section Reference
	Area Stigma?	Scenic Vista Stigma?	Nuisance Stigma?	
Base Model	No	No	No	<i>Section 4</i>
View Stability	Not tested	No	Not tested	<i>Section 5.1</i>
Distance Stability	No	Not tested	No	<i>Section 5.1</i>
Continuous Distance	No	No	No	<i>Section 5.2</i>
All Sales	No	No	Limited	<i>Section 5.3</i>
Temporal Aspects	No	No	No	<i>Section 5.4</i>
Orientation	No	No	No	<i>Section 5.5</i>
Overlap	No	Limited	No	<i>Section 5.6</i>
Repeat Sales	No	Limited	No	<i>Section 6</i>
Sales Volume	No	Not tested	No	<i>Section 7</i>

"No"..... *No statistical evidence of a negative impact*

"Yes"..... *Strong statistical evidence of a negative impact*

"Limited"..... *Limited and inconsistent statistical evidence of a negative impact*

"Not tested"..... *This model did not test for this stigma*

### 8.1. Area Stigma

Area Stigma is defined as a concern that the general area surrounding a wind energy facility will appear more developed, which may adversely affect home values in the local community regardless of whether any individual home has a view of the wind turbines. Though these impacts might be expected to be especially severe at close range to the turbines, the impacts could conceivably extend for a number of miles around a wind facility. Modern wind turbines are visible from well outside of five miles in many cases, so if an Area Stigma exists, it is possible that all of the homes in the study areas inside of five miles would be affected.

As summarized in Table 33, Area Stigma is investigated with the Base, Distance Stability, Continuous Distance, All Sales, Temporal Aspects, Orientation, and Overlap hedonic models. It is also tested, somewhat differently, with the Repeat Sales and Sales Volume analyses. In each case, if an Area Stigma exists, it is expected that the sales prices (and/or sales volume) of homes



located near wind facilities would be broadly affected by the presence of those facilities, with effects decreasing with distance.

The Base Model finds little evidence of an Area Stigma, as the coefficients for the DISTANCE variables are all relatively small and none are statistically different from zero. For homes in this sample, at least, there is no statistical evidence from the Base Model that the distance from a home to the nearest wind turbine impacts sales prices, regardless of the distance band. Perhaps a more direct test of Area Stigma, however, comes from the Temporal Aspects Model. In this model, homes in all distance bands that sold after wind facility announcement are found to sell, on average, for prices that are not statistically different from those for homes that sold more than two years prior to wind facility announcement. Again, no persuasive evidence of an Area Stigma is evident.

The Repeat Sales and Sales Volume Models also investigate Area Stigma. The Repeat Sales Model's 354 homes, each of which sold once before facility announcement and again after construction, show average inflation-adjusted annual appreciation rates that are small and not statistically different from zero. If homes in all study areas were subject to an Area Stigma, one would expect a negative and statistically significant intercept term. Similarly, if homes in any individual study area experienced an Area Stigma, the fixed effect terms would be negative and statistically significant. Neither of these expectations is borne out in the results. The Sales Volume Model tells a similar story, finding that the rate of residential transactions is either not significantly different between the pre- and post-announcement periods, or is greater in later periods, implying, in concert with the other tests, that increased levels of transactions do not signify a rush to sell, and therefore lower prices, but rather an increase in the level of transactions with no appreciable difference in the value of those homes.

The All Sales, Distance Stability, Continuous Distance, Orientation, and Overlap Models corroborate these basic findings. In the All Sales and Distance Stability Models, for example, the DISTANCE coefficients for homes that sold outside of one mile but within five miles, compared to those that sold outside of five miles, are very similar: they differ by no more than 2%, and this small disparity is not statistically different from zero. The same basic findings resulted from the Orientation and Overlap Models. Further, homes with No View as estimated in the All Sales Model are found to appreciate in value, after adjusting for inflation, when compared to homes that sold before wind facility construction (0.02, *p* value 0.06); an Area Stigma effect should be reflected as a negative coefficient for this parameter. Finally, despite using all 4,937 cases in a single distance variable and therefore having a correspondingly small standard error, the Continuous Distance Model discovers no measurable relationship between distance from the nearest turbine and the value of residential properties.

Taken together, the results from these models are strikingly similar: there is no evidence of a widespread and statistically significant Area Stigma among the homes in this sample. Homes in these study areas are not, on average, demonstrably and measurably stigmatized by the arrival of a wind facility, regardless of when they sold in the wind project development process and regardless of whether those homes are located one mile or five miles away from the nearest wind facility.

Drawing from the previous literature on environmental disamenities discussed in Section 2.1, one likely explanation for this result is simply that any effects that might exist may have faded to a level indistinguishable from zero at distances outside of a mile from the wind facilities. For other disamenities, some of which would seemingly be more likely to raise concerns, effects have been found to fade quickly with distance. For example, property value effects near a chemical plant have been found to fade outside of two and a half miles (Carroll et al., 1996), near a lead smelter (Dale et al., 1999) and fossil fuel plants (Davis, 2008) outside of two miles, and near landfills and confined animal feeding operations outside of 2,400 feet and 1,600 feet, respectively (Ready and Abdalla, 2005). Further, homes outside of 300 feet (Hamilton and Schwann, 1995) or even as little as 150 feet (Des-Rosiers, 2002) from a high voltage transmission line have been found to be unaffected. A second possible explanation for these results could be related to the view of the turbines. In the sample used for this analysis, a large majority of the homes outside of one mile ( $n = 4,812$ ) that sold after wind-facility construction commenced cannot see the turbines ( $n = 4,189$ , 87%), and a considerably larger portion have – at worst – a minor view of the turbines ( $n = 4,712$ , 98%). Others have found that the sales prices for homes situated at similar distances from a disamenity (e.g., HVTL) depend, in part, on the view of that disamenity (Des-Rosiers, 2002). Similarly, research has sometimes found that annoyance with a wind facility decreases when the turbines cannot be seen (Pedersen and Wayne, 2004). Therefore, for the overwhelming majority of homes outside of a mile that have either a minor rated view or no view at all of the turbines, the turbines may simply be out of sight, and therefore, out of mind.

## 8.2. Scenic Vista Stigma

Scenic Vista Stigma is defined as concern that a home may be devalued because of the view of a wind energy facility, and the potential impact of that view on an otherwise scenic vista. It has as its basis an admission that home values are, to some degree, derived from the quality of what can be seen from the property and that if those vistas are altered, sales prices might be measurably affected. The Base, View Stability, Continuous Distance, All Sales, Temporal Aspects, Orientation, Overlap, and Repeat Sales Models each test whether Scenic Vista Stigma is present in the sample.

The Base Model, as well as subsequent Alternative Hedonic Models, demonstrates persuasively that the quality of the scenic vista – absent wind turbines – impacts sales prices. Specifically, compared to homes with an AVERAGE VISTA, those having a POOR or a BELOW AVERAGE rating are estimated to sell for 21% ( $p$  value 0.00) and 8% ( $p$  value 0.00) less, on average. Similarly, homes with an ABOVE AVERAGE or PREMIUM rating are estimated to sell for 10% ( $p$  value 0.00) and 13% ( $p$  value 0.00) more than homes with an AVERAGE vista rating. Along the same lines, homes in the sample with water frontage or situated on a cul-de-sac sell for 33% ( $p$  value 0.00) and 10% ( $p$  value 0.00) more, on average, than those homes that lack these characteristics. Taken together, these results demonstrate that home buyers and sellers consistently take into account what can be seen from the home when sales prices are established, and that the models presented in this report are able to clearly identify those impacts.<sup>103</sup>

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<sup>103</sup> Of course, cul-de-sacs and water frontage bestow other benefits to the home owner beyond the quality of the scenic vista, such as safety and privacy in the case of a cul-de-sac, and recreational potential and privacy in the case of water frontage.

Despite this finding, those same hedonic models are unable to identify a consistent and statistically significant Scenic Vista Stigma associated with wind facilities. Home buyers and sellers, at least among this sample, do not appear to be affected in a measurable way by the visual presence of wind facilities. Regardless of which model was estimated, the value of homes with views of turbines that were rated MODERATE, SUBSTANTIAL, or EXTREME are found to be statistically indistinguishable from the prices of homes with no view of the turbines. Specifically, the 25 homes with EXTREME views in the sample, where the home site is “unmistakably dominated by the [visual] presence of the turbines,” are not found to have measurably different property values, and neither are the 31 homes with a SUBSTANTIAL view, where “the turbines are dramatically visible from the home.”<sup>104</sup> The same finding holds for the 106 homes that were rated as having MODERATE views of the wind turbines. Moreover, the Orientation and Overlap Models show that neither the orientation of the home with respect to the view of wind turbines, nor the overlap of that view with the prominent scenic vista, have measurable impacts on home prices.

The All Sales Model compares homes with views of the turbines (in the post-construction period) to homes that sold before construction (when no views were possible), and finds no statistical evidence of adverse effects within any VIEW category. Moreover, when a *t*-Test is performed to compare the NO VIEW coefficient to the others, none of the coefficients for the VIEW ratings are found to be statistically different from the NO VIEW homes. The Repeat Sales Model comes to a similar result, with homes with MODERATE views appreciating at a rate that was not measurably different from that of homes with no views (0.03, *p* value 0.29). The same model also finds that homes with SUBSTANTIAL/EXTREME views appreciate at a rate 2% slower per year (*p* value 0.09) than their NO VIEW peers. Homes situated inside of one mile, however, are found to appreciate at a rate 3% more (*p* value 0.01) than reference homes located outside of five miles. Eight of the nine homes situated inside of one mile had either a SUBSTANTIAL or EXTREME view. Therefore, to correctly interpret these results, one would add the two coefficients for these homes, resulting in a combined 1% increase in appreciation as compared to the reference homes situated outside of five miles with no view of turbines, and again yielding no evidence of a Scenic Vista Stigma.

Although these results are consistent across most of the models, there are some individual coefficients from some models that differ. Specifically, homes with MINOR rated views in the Overlap and Repeat Sales Models are estimated to sell for 3% less (*p* value 0.10) and appreciate at a rate 2% less (*p* value 0.02) than NO VIEW homes. Taken at face value, these MINOR VIEW findings imply that homes where “turbines are visible, but, either the scope is narrow, there are many obstructions, or the distance between the home and the facility is large” are systematically impacted in a modest but measurable way. Homes with more dramatic views of a wind facility in the same models, on the other hand, are found to not be measurably affected. Because of the counterintuitive nature of this result, and because it is contradicted in the results of other models presented earlier, it is more likely that there is some aspect of these homes that was not modeled appropriately in the Overlap and Repeat Sales Models, and that the analysis is picking up the effect of omitted variable(s) rather than a systematic causal effect from the wind facilities.

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<sup>104</sup> See Section 3.2.3 and Appendix C for full description of VIEW ratings.

Taken together, the results from all of the models and all of the VIEW ratings support, to a large degree, the Base Model findings of no evidence of a Scenic Vista Stigma. Although there are 160 residential transactions in the sample with more dramatic views than MINOR, none of the model specifications is able to find any evidence that those views of wind turbines measurably impacted average sales prices, despite the fact that those same models consistently find that home buyers and sellers place value on the quality of the scenic vista.

### 8.3. Nuisance Stigma

Nuisance Stigma is defined as a concern that factors that may occur in close proximity to wind turbines, such as sound and shadow flicker, will have a unique adverse influence on home values. If these factors impact residential sales prices, those impacts are likely to be concentrated within a mile of the wind facilities. The Base, Distance Stability, Continuous Distance, All Sales, Temporal Aspects, Orientation, Overlap, Repeat Sales, and Sales Volume Models all investigate the possible presence of a Nuisance Stigma.

The Base Model finds that those homes within 3000 feet and those between 3000 feet and one mile of the nearest wind turbine sold for roughly 5% less than similar homes located more than five miles away, but that these differences are not statistically significant ( $p$  values of 0.40 and 0.30, respectively). These results remain unchanged in the Distance Stability Model, as well as in the Orientation and Overlap Models. Somewhat similarly, in the All Sales Model, when all transactions occurring after wind facility announcement are assumed to potentially be impacted (rather than just those occurring after construction, as in the Base Model), and a comparison is made to the average of all transactions occurring pre-announcement (rather than the average of all transactions outside of five miles, as in the Base Model), these same coefficients grow to -6% ( $p$  value 0.23) and -8% ( $p$  value 0.08) respectively. Although only one of these coefficients was statistically significant, they are large enough to warrant further scrutiny.

The Temporal Aspects Model provides a clearer picture of these findings. It finds that homes that sold prior to wind facility announcement and that were situated within one mile of where the turbines were eventually located sold, on average, for between 10% and 13% less than homes located more than five miles away and that sold in the same period. Therefore, the homes nearest the wind facility's eventual location were already depressed in value before the announcement of the facility. Most telling, however, is what occurred after construction. Homes inside of one mile are found to have inflation-adjusted sales prices that were either statistically undistinguishable from, or in some cases greater than, pre-announcement levels. Homes sold in the first two years after construction, for example, have higher prices (0.07,  $p$  value 0.32), as do those homes that sold between two and four years after construction (0.13,  $p$  value 0.06) and more than four years after construction (0.08,  $p$  value 0.24). In other words, there is no indication that these homes experienced a decrease in sales prices after wind facility construction began. Not only does this result fail to support the existence of a Nuisance Stigma, but it also indicates that the relatively large negative coefficients estimated in the Base and All Sales Models are likely caused by conditions that existed prior to wind facility construction and potentially prior to facility announcement.<sup>105</sup>

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<sup>105</sup> See footnote 82 on page 46 for a discussion of possible alternative explanations to this scenario.

These results are corroborated by the Continuous Distance Model, which finds no statistically significant relationship between an inverse DISTANCE function and sales prices (-0.01, sig 0.46). Similarly, in the Repeat Sales Model, homes within one mile of the nearest turbine are not found to be adversely affected; somewhat counter-intuitively, they are found to appreciate faster (0.03, *p* value 0.01) than their peers outside of five miles. Finally, the Sales Volume analysis does not find significant and consistent results that would suggest that the ability to sell one's home within one mile of a wind facility is substantially impacted by the presence of that facility.

Taken together, these models present a consistent set of results: the sales prices of homes in this sample that are within a mile of wind turbines, where various nuisance effects have been posited, are not measurably affected compared to those homes that are located more than five miles away from the facilities or that sold well before the wind projects were announced. These results imply that widespread Nuisance Stigma effects are either not present in the sample, or are too small or sporadic to be statistically identifiable.

Though these results may appear counterintuitive, it may simply be that property value impacts fade rapidly with distance, and that few of the homes in the sample are close enough to the subject wind facilities to be substantially impacted. As discussed earlier, studies of the property value impacts of high voltage transmission lines often find that effects fade towards zero at as little distance as 200 feet (see, e.g., Gallimore and Jayne, 1999; Watson, 2005). None of the homes in the present sample are closer than 800 feet to the nearest wind turbine, and all but eight homes are located outside of 1000 feet of the nearest turbine. It is therefore possible that, if any effects do exist, they exist at very close range to the turbines, and that those effects are simply not noticeable outside of 800 feet. Additionally, almost half of the homes in the sample that are located within a mile of the nearest turbine have either no view or a minor rated view of the wind facilities, and some high voltage transmission line (HVTL) studies have found a decrease in adverse effects if the towers are not visible (Des-Rosiers, 2002) and, similarly, decreases in annoyance with wind facility sounds if turbines cannot be seen (Pedersen and Waye, 2004). Finally, effects that existed soon after the announcement or construction of the wind facilities might have faded over time. More than half of the homes in the sample sold more than three years after the commencement of construction, while studies of HVTLs have repeatedly found that effects fade over time (Kroll and Priestley, 1992) and studies of attitudes towards wind turbines have found that such attitudes often improve after facility construction (Wolsink, 1989). Regardless of the explanation, the fact remains that, in this sizable sample of residential transactions, no persuasive evidence of a widespread Nuisance Stigma is found, and if these impacts do exist, they are either too small or too infrequent to result in any widespread and consistent statistically observable impact.

## 9. Conclusions

Though surveys generally show that public acceptance towards wind energy is high, a variety of concerns with wind development are often expressed at the local level. One such concern that is often raised in local siting and permitting processes is related to the potential impact of wind projects on the property values of nearby residences.

This report has investigated the potential impacts of wind power facilities on the sales prices of residential properties that are in proximity to and/or that have a view of those wind facilities. It builds and improves on the previous literature that has investigated these potential effects by collecting a large quantity of residential transaction data from communities surrounding a wide variety of wind power facilities, spread across multiple parts of the U.S. Each of the homes included in this analysis was visited to clearly determine the degree to which the wind facility was visible at the time of home sale and to collect other essential data. To frame the analysis, three potentially distinct impacts of wind facilities on property values are considered: Area, Scenic Vista, and Nuisance Stigma. To assess these potential impacts, the authors applied a base hedonic model, explored seven alternative hedonic models, conducted a repeat sales analysis, and evaluated possible impacts on sales volumes. The result is the most comprehensive and data-rich analysis to date on the potential impacts of wind projects on nearby property values.

Although each of the analysis techniques used in this report has strengths and weaknesses, the results are strongly consistent in that each model fails to uncover conclusive evidence of the presence of any of the three property value stigmas. Based on the data and analysis presented in this report, no evidence is found that home prices surrounding wind facilities are consistently, measurably, and significantly affected by either the view of wind facilities or the distance of the home to those facilities. Although the analysis cannot dismiss the possibility that individual or small numbers of homes have been or could be negatively impacted, if these impacts do exist, they are either too small and/or too infrequent to result in any widespread and consistent statistically observable impact. Moreover, to the degree that homes in the present sample are similar to homes in other areas where wind development is occurring, the results herein are expected to be transferable.

Finally, although this work builds on the existing literature in a number of respects, there remain a number of areas for further research. The primary goal of subsequent research should be to concentrate on those homes located closest to wind facilities, where the least amount of data are available. Additional research of the nature reported in this paper could be pursued, but with a greater number of transactions, especially for homes particularly close to wind facilities. Further, it is conceivable that cumulative impacts might exist whereby communities that have seen repetitive development are affected uniquely, and these cumulative effects may be worth investigating. A more detailed analysis of sales volume impacts may also be fruitful, as would an assessment of the potential impact of wind facilities on the length of time homes are on the market in advance of an eventual sale. Finally, it would be useful to conduct a survey of those homeowners living close to existing wind facilities, and especially those residents who have bought and sold homes in proximity to wind facilities after facility construction, to assess their opinions on the impacts of wind project development on their home purchase and sales decisions.

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## **Appendix A: Study Area Descriptions**

The analysis reported in the body of the report used data from ten different wind-project study areas, across nine different states and 14 counties, and surrounding 24 different wind facilities. Each of the study areas is unique, but as a group they provide a good representation of the range of wind facility sizes, hub heights, and locations of recent wind development activity in the U.S. (see Figure A - 1 and Table A - 1). This appendix describes each of the ten study areas, and provides the following information: a map of the study area; a description of the area; how the data were collected; statistics on home sales prices in the sample and census-reported home values for the towns, county, and state that encompass the area; data on the wind facilities contained within the study area; and frequency tables for the variables of interest (i.e., views of turbines, distance to nearest turbine ,and development period).