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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_2 emissions or 30% of all worldwide carbon dioxide (CO_2) emissions, and 72% of CO_2 emissions from power generation (one gigaton = one billion tons; one metric ton = 2,204 pounds.)[1] 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_2, bringing coal's total burden of CO_2 emissions to 41% of worldwide CO_2 emissions in 2005.[1]

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.[1] In this same time period, worldwide CO_2 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.[1]

In the United States, coal has produced approximately half of the nation's electricity since 1995,[2] and demand for electricity in the United States is projected to grow 1.3% per year from 2005 to 2030, to 5,947 TWh.[1] 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).[1] Other agencies show similar projections; the U.S. Energy Information Administration (EIA)

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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.[3]

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.[1,4] 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).[5]

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).[2] Two-thirds of this is found in four countries: U.S. 28%; Russia 19%; China 14%, and India 7%.[6] In the United States, coal is mined in 25 states.[2] Much of the new mining in Appalachia is projected to come from mountaintop removal (MTR).[2]

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.[7] 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.[7] 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.[8–11]

Recent multi-Hubbert cycle analysis estimates global peak coal production for 2011 and U.S. peak coal production for 2015.[12] 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.[13] In 2010, it remained in the \$70+/ton range.

Coal burning produces one and a half times the CO_2 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_2 emissions.[13] 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.[14]

Thus, in the United States in 2005, coal produced 50% of the nation's electricity but 81% of the CO_2 emissions.[1] For 2030, coal is projected to produce 53% of U.S. power and 85% of the U.S. CO_2 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_2O) 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.[15–19] Coal combustion also results in emissions of NO_x, sulfur dioxide (SO_2), the particulates PM_{10} and $PM_{2.5}$, and mercury; all of which negatively affect air quality and public health.[20–23]

In addition, 70% of rail traffic in the United States is dedicated to shipping coal, and rail transport is associated with accidents and deaths.[20] 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.[24] 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.[20] 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_x, SO_2, $PM_{2.5}$, 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_2equivalent (CO_2e),[20] 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."[20] To be consistent with the NRC report, this work uses a low value of \$10/ton CO_2e and a high value of \$100/ton CO_2e.

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$, or \$7.5 million in 2008 US$.[20]

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.[2,20] 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.[25] Health-related impact pathways were monetized using the value of disability-adjusted life-years from ExternE,[26] and the social costs of carbon.[20] 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_2 emissions that year.
2. In the United States, coal produces just over 50% of the electricity, but generates over 80% of the CO_2 emissions from the utility sector.[2]
3. Coal burning produces one and a half times more CO_2 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.[4]
5. Today, 70% of rail traffic in the United States is dedicated to shipping coal.[20] 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.[27] 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.[14]

In China, underground mining accidents cause 3,800–6,000 deaths annually,[28] 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.[29]

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.[30] Since 1900 coal workers' pneumoconiosis has killed over 200,000 in the United States.[14] 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.[31]

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,[32] completely altering some 1.4 million acres, burying 2,000 miles of streams.[33] In Kentucky, alone, there are 293 MTR sites, over 1,400 miles of streams damaged or destroyed, and 2,500 miles of streams polluted.[34–36] Valley fill and other surface mining practices associated with MTR bury headwater streams and contaminate surface and groundwater with carcinogens and heavy metals[16] and are associated with reports of cancer clusters,[37] 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.[38] 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.[38] They estimated that each year, between 6 and 6.9 million tons of CO_2e 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[38] 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_2e from soil and 27.5 million tons CO_2e from mining spoil. In this analysis, the 6 million tons CO_2e from forest plants and forest litter represents our low and best estimates for all coal use, and 37 million tons CO_2e (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 Campell studied, 90.5% of coal was used for electricity, so we attribute 90.5% of these emissions to coal-derived power.[2] To monetize 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_2e 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_2e; and the low estimate was calculated using the point estimate for emissions and the \$10/ton low estimate for the social cost of carbon.[20] 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.[39,40]

Blasting to clear mountain ridges adds an additional assault to surrounding communities.[16] 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.[41]

Methane

In addition to being a heat-trapping gas of high potency, methane adds to the risk of explosions, and fires at mines.[20,42] As of 2005, global atmospheric methane levels were approximately 1,790 parts per billion (ppb), which is an 27 ppb increase over 1998.[43] Methane is emitted during coal mining and it is 25 times more potent than CO_2 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_2, an effect that is not fully assessed in this equivalency value.[43]

According to the EIA,[2] 71,100,000 tons CO_2e 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	1. Methane emissions from coal leading to climate change	
		2. Threats remaining from abandoned mine lands	2. Remaining damage from abandoned mine lands	
MTR mining	1. Tourism loss	1. Contaminated streams	1. Loss of biodiversity	
	2. Significantly lower property values	2. Direct trauma in surrounding communities	2. Sludge and slurry ponds	
	3. Cost to taxpayers of environmental mitigation and monitoring (both mining and disposal stages)	3. Additional mortality and morbidity in coal communities due to increased levels of air particulates associated with MTR mining (vs. underground mining)	3. Greater levels of air particulates	
	4. Population declines	4. Higher stress levels	4. Loss and contamination of streams	
Coal mining	1. Opportunity costs of bypassing other types of economic development (especially for MTR mining)	1. Workplace fatalities and injuries of coal miners	1. Destruction of local habitat and biodiversity to develop mine site	1. Infrastructure damage due to mudslides following MTR
	2. Federal and state subsidies of coal industry	2. Morbidity and mortality of mine workers resulting from air pollution (e.g., black lung, silicosis)	2. Methane emissions from coal leading to climate change	2. Damage to surrounding infrastructure from subsidence
	3. Economic boom and bust cycle in coal mining communities	3. Increased mortality and morbidity in coal communities due to mining pollution	3. Loss of habitat and streams from valley fill (MTR)	3. Damages to buildings and other infrastructure due to mine blasting
	4. Cost of coal industry litigation	4. Increased morbidity and mortality due to increased air particulates in communities proximate to MTR mining	4. Acid mine drainage	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. Local health impacts of heavy metals in coal slurry	6. Water pollution from runoff and waste spills	
	6. Loss of income from small scale forest gathering and farming (e.g., wild ginseng, mushrooms) due to habitat loss	7. Health impacts resulting from coal slurry spills and water contamination	7. Remaining damage from abandoned mine lands	
	7. Loss of tourism income	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	
	8. Lost land required for waste disposal	9. Mental health impacts		
	9. Lower property values for homeowners	10. Dental health impacts reported, possibly from heavy metals		
	10. Decrease in mining jobs in MTR mining areas	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_2 and NO_x derived N_2O 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_x 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_2	
		4. See Levy *et al.*[21]	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.[20] Life cycle assessment results, based on 2004 data and emissions from a subset of power plants, indicated 0.037 kg of CO_2e 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.[47] Their volume and composition have not been calculated.[48] For Kentucky, the number of known waste and slurry ponds alongside MTR sites and processing plants is 115.[49] These

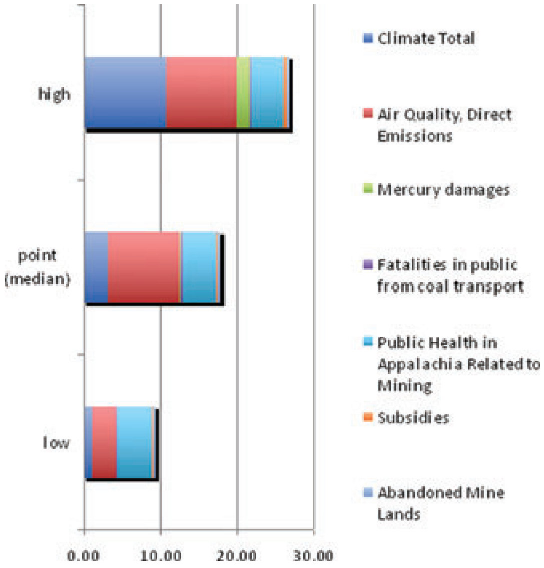

Figure 1. This graph shows the best estimates of the externalities due to coal, along with low and high estimates, normalized to ¢ per kWh of electricity produced. (In color in *Annals* online.)

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.[50] Coal slurry is the byproduct of these coal refining plants. In West Virginia, there are currently over 110 billion gallons of coal slurry permitted for 126 impoundments.[49,51] 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.[48] 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.[52,53]

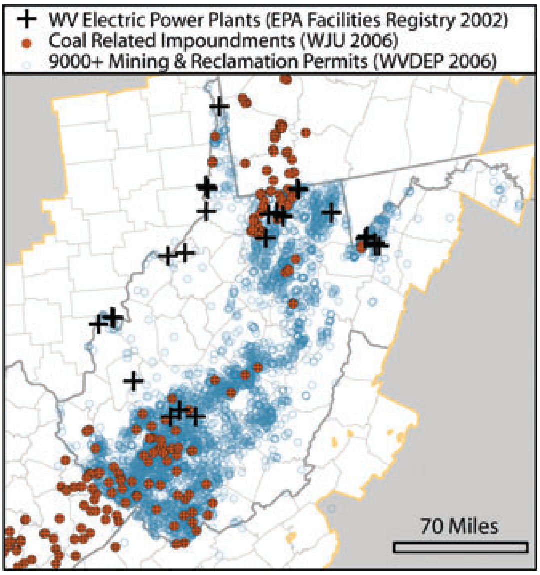

Figure 2. Electric power plants, impoundments (sludge and slurry ponds, CCW, or "fly ash"), and sites slated for reclamation in West Virginia.[44–46] (In color in *Annals* online.) Source: Hope Childers, Wheeling Jesuit University.

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.[47,54] 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.[55] 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.[56]

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.[57] Based on a series of state estimates, approximately 20% of the total is injected into abandoned coal mines.[58]

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.[47]

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.[16,50]

Spath and colleagues[50] found that these emissions are small in comparison to the air emissions. However, a more recent study performed by Koornneef and colleagues[59] 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.[16,17,60,61] 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.[48] 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 Ecoinvent database.[25] The eco-indicator impact assessment method was used to estimate health damages in disability-adjusted life years due to these emissions,[25] and were valued using the VSL-year.[26] 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).[25] 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,[62] lung cancer mortality rates,[60] and mortality from heart, respiratory, and kidney disease[17] 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[18] 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 LBWs infant by 16% relative to women residing in counties without coal mining.[63] LBW and preterm births are elevated,[64] and children born with extreme LBW fare worse than do children with normal birth weights in almost all neurological assessments;[65] as adults, they have more chronic diseases, including hypertension and diabetes mellitus.[66] Poor birth outcomes are especially elevated in areas with MTR mining as compared with areas with other forms of mining.[67] MTR mining has increased in the areas studied, and is occurring close to population centers.[62]

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

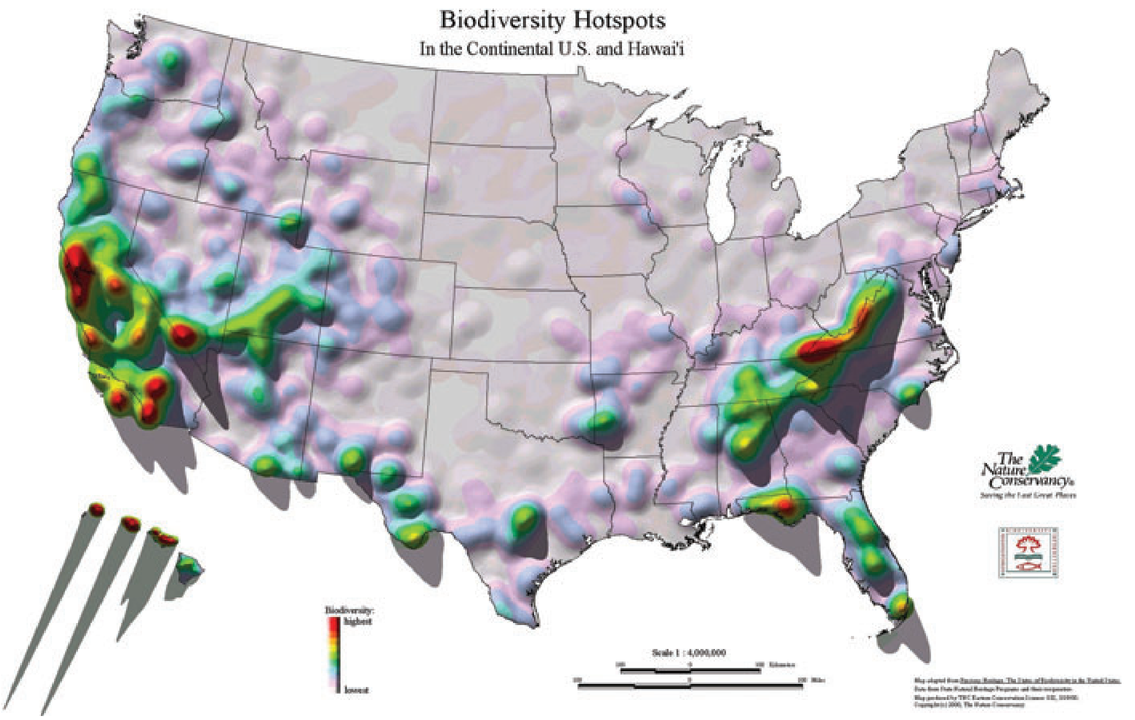

Figure 3. Areas of highest biological diversity in the continental United States. Source: The Nature Conservancy, Arlington, VA. (In color in *Annals* online.)

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

Using the VSL of \$7.5 million,[20] the unadjusted mortality rate, and the estimate that 91% of coal during these years was used for electricity,[2] 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.[16,20]

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

Imperiled aquatic ecosystems

Existence of viable aquatic communities in valley fill permit sites was first elucidated in court testimony leading to the "Haden decision."[70] 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.[71] 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.[72] The EPA recommends that stream conductivity not exceed 500 microsiemens per cm (*u*S/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 *u*S/cm.[72]

Meanwhile, even levels below 500 *u*S/cm were shown to significantly affect the abundance and composition of macroinvertebrates, such as mayflies and caddis flies.[73] "Sharp declines" were found in some stream invertebrates where only 1% of the watershed had been mined.[74,75]

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.[76]

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.[77] 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.[78]

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.[41] This dust presents an additional burden in terms of respiratory and cardiovascular disease, some of which may have been captured by Hendryx and colleagues.[17–19,60,62,67,68,79]

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.[20]

The NRC report[20] 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.[19]

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.[27] 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.[19,27] There are 6,300 MTR and surface mining jobs in West Virginia, representing 0.7–0.8% of the state labor force.[2] 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.[19,80]

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_2, methane, particulates and oxides of nitrogen, oxides of sulfur, mercury, and a wide range of carcinogenic chemicals and heavy metals.[20]

Long-range air pollutants and air quality. Data from the U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID)[81] and National Emissions Inventory (NEI)[82] demonstrates that coal power is responsible for much of the U.S. power generation-related emissions of $PM_{2.5}$ (51%), NO_x (35%), and SO_2 (85%). Along with primary emissions of the particulates, SO_2 and NO_x contribute to increases in airborne particle concentrations through secondary transformation processes.[20,21,83]

Studies in New England[84] 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_2 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 nonfatal 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.[85] A review[83] of the epidemiology of airborne particles documented that exposure to $PM_{2.5}$ 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 $PM_{2.5}$ were at higher risk.[86] Particulates are a cause of lung and heart disease, and premature death,[83] and increase hospitalization costs. Diabetes mellitus enhances the health impacts of particulates[87] and has been implicated in sudden infant death syndrome.[88] 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.[89]

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.*[90] used year-to-year changes in $PM_{2.5}$ concentrations instead of assigning each city a constant $PM_{2.5}$ concentration. To construct one composite estimate for mortality risk from $PM_{2.5}$, the reanalysis also allowed for yearly lags in mortality effects from exposure to $PM_{2.5}$, and revealed that the relative risk of mortality increases by 1.1 per 10 $\mu g/m^3$ increase in $PM_{2.5}$ the year of death, but just 1.025 per 10 $\mu g/m^3$ increase in $PM_{2.5}$ the year before death. This indicates that most of the increase in risk of mortality from $PM_{2.5}$ 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 $PM_{2.5}$ and that all levels of $PM_{2.5}$ pose a risk to human health.[91]

Thus, prevention strategies should be focused on continuous reduction of $PM_{2.5}$ 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 $\mu g/m^3$, arguing that there is no evidence for harm below this level.[92] The results of the Schwartz *et al.*[90] study directly contradict this line of reasoning.

Risk assessment. The risk assessment performed by the NRC,[20] 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 $PM_{2.5}$, PM_{10}, SO_2, NO_x, 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_2 were the most damaging of the pollutants affecting air quality, and 99% of this was due to SO_2 in the particle form.[20] The NRC study found that over 90% of the damages due to air quality are from $PM_{2.5}$-related mortality, which implies that these damages included approximately 8,158 excess mortality cases.[20] For the state of Kentucky alone, for each ton of SO_2 removed from the stack, the NRC (2009)[20] 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[26] 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,[83] which provides a low estimate for increases in mortality risk with increases in $PM_{2.5}$ exposure and is an outlier when compared to other studies examining the $PM_{2.5}$–mortality relationship.[6,87] Had they used the result of the more recent study by Schwartz *et al.*,[90] which was used in a similar study by Levy *et al.*,[21] or the number from Dockery *et al.*,[93] the value they calculated would have been approximately three times higher,[20] 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 $PM_{2.5}$ and mortality, and is now widely accepted,[21,94] we use it here to derive our best and high estimate, and the Pope and Dockery,[83] 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.[95] In an analysis by Jaworkski *et al.*,[95] 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.[95] Anthropogenic contributions of nitrogen are equal to the natural sources, doubling this form of fertilization of soils and water bodies.[96]

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[97] 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_2O from land clearing is a heat-trapping gas[38,42] and adds to the nitrogen deposited in soils and water bodies. The nitrogen is also a contributor to fresh and sea water acidification.[98–100] Other factors include the loss of wetlands that filter discharges.[98–100]

The economic losses from HABs are estimated to be over $82 million/year in the United States, based on the most prominent episodes.[101,102] 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.[98–100]

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[103] 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_2, sulfates contribute to acid rain, decreased visibility, and have a greenhouse cooling influence.[20]

The long-term Hubbard Brook Ecosystem Study[104] 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.[105]

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.[106]

Mercury. Coal combustion in the U.S. releases approximately 48 tons of the neurotoxin mercury each year.[54] 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.[107] 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.[107] 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.[107]

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.*[22,23] 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.[108] Rice *et al.*[109] 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[22,23] 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_2-e/year.[109] The International Energy Agency's Reference Scenario estimates that worldwide CO_2 emissions will increase by 57% between 2005 and 2030, or 1.8% each year, to 41,905 Mt.[1] In the same time period, CO_2 emissions from coal-generated power are projected to increase 76.6% to 13,884 Mt.[1]

In 2005, coal was responsible for 82% of the U.S.'s GHG emissions from power generation.[110] In addition to direct stack emissions, there are methane emissions from coal mines, on the order of 3% of the stack emissions.[110] There are also additional GHG emissions from the other uses of coal, approximately 139 Mt CO_2.[1]

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.[111–113] 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_2.[111]

Climate change

Since the 1950s, the world ocean has accumulated 22 times as much heat as has the atmosphere,[114] and the pattern of warming is unmistakably attributable to the increase in GHGs.[115] 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.[116,117] 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[2] estimated that 1.97 billion tons of CO_2 and 9.3 million tons CO_2e of N_2O 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[81] on electricity produced from lignite. The low, mean, and high energy density values for lignite[5] was then used to calculate the amount of lignite consumed. The Cooke *et al.*[118] emissions factor was used to estimate black carbon emissions based on lignite use and the Hansen *et al.*[111] global temperature potential was used to convert these emissions to CO_2e. This resulted in an estimate of 1.5 million tons CO_2e 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.[119] 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.[120]

The total costs of climate change damages from coal-derived power, including black carbon, CO_2 and N_2O 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[121] 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_2 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.[5]

		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_2 emitted (kg/hr)	466,000	63,600	414,903	54,518	369,000	46,800	52,202	415,983	51,198
	CO_2 captured at 90%, (kg/h)	0	573.000	0	490662	0	422000	469817	0	460782
	CO_2 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	$640,000,000	$1,115,000,000	$665,000,000	$1,070,000,000	$680,000,000	$1,045,000,000	$950,000,000	$715,000,000	$945,000,000
	Inv. Charce ¢/kWh @ 15.1%	2.6	4.52	2.7	4.34	2.76	4.24	3.85	2.9	3.83
	Fuel ¢/kWh @ $1.50/MMBtu	1.49	2.04	1.33	1.75	1.18	1.5	1.67	1.33	1.64
	O&M ¢/kWh	0.75	1.6	0.75	1.6	0.75	1.6	1.45	0.9	1.05
	COE ¢/kWh	4.84	8.16	4.78	7.69	4.69	7.34	8.98	5.13	6.52
	Cost of CO_2 avoided vs. same technology w/o capture ($/ton)		41.3		40.4		41.1	30.3		19.3
	Cost of CO_2 avoided vs. supercritical technology w/o capture ($/ton)		48.2		40.4		34.8	30.3		24
	Energy penalty		1,365,384,615		1,313,996,128		1,274,390,244			1,230,553,038

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.[4,42]

Retrofitting old plants—the largest source of CO_2 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).[5]

The U.S. Department of Energy estimates that an underground volume of 30,000 km^2 will be needed per year to reduce the CO_2 emissions from coal by 20% by 2050 (the total land mass of the continental U.S. (48 states) is 9,158,960 km^2).[122]

The safety and ensurability of scaling up the storage of the billion tons of CO_2 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_2 emissions in the United States" (p. 7).[123]

Health and environmental risks of CCS

The Special IPCC Report on Carbon Dioxide Capture and Storage[42] lists the following concerns for CCS in underground terrestrial sites:

1. Storing compressed and liquefied CO_2 underground can acidify saline aquifers (akin to ocean acidification) and leach heavy metals, such as arsenic and lead, into ground water.[42]
2. Acidification of ground water increases fluid-rock interactions that enhance calcite dissolution and solubility, and can lead to fractures in

limestone ($CaCO_3$) and subsequent releases of CO_2 in high concentrations.[124]

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 CO_2 are toxic to plants and animals.[42]
    a. The 2006 Mammoth Mountain, CA release left dead stands of trees.[124]
6. Microbial communities may be altered, with release of other gases.[42]

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.[5] It does appear that complete rebuilds are more economically attractive than retrofits, and that "carbon-capture ready" plants are not economically desirable to build.[5]

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.[126] 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.[126]

The U.S. Federal Government provides subsides for electricity and mining activities, and these have been tallied by both the EIA and the Environmental Law Institute.[2,127,128] 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.[129] There are over 1,700 old abandoned mines in Pennsylvania, alone.[14] 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.

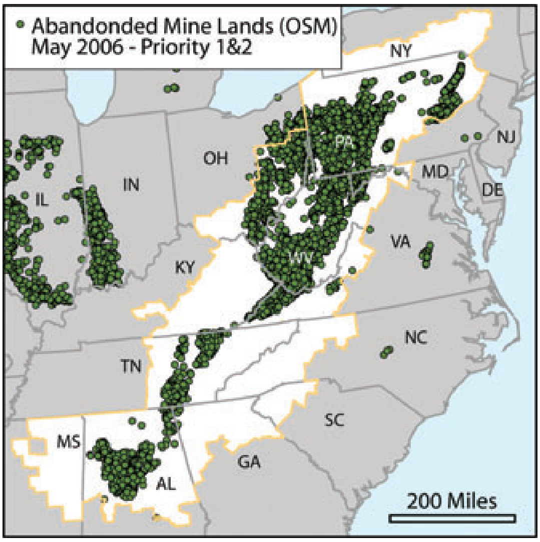

Figure 4. Current high-priority abandoned mine land reclamation sites from Alabama to Pennsylvania.[129] (In color in *Annals* online.) Source: Hope Childers, Wheeling Jesuit University.

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.[129] Despite the more than \$7.4 billion that has been collected as of September 30, 2005, there is a growing backlog of unfunded projects.[51] 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[129] 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_2 and N_2O	$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[56] (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_2 and N_2O	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.[130] 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,[131] and weak economic conditions in turn are powerful predictors of social and health disadvantages.[130,132]

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_2, 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

µPa	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	*Diagnostic and Statistical Manual of Mental Disorders*, 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

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

Term	Definitions
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.

Source: HPA, 2009.

SECTION 2
Methodology

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

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?
- **W**hat 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) Shout (0.5 feet)	100	
N.Y. subway station Heavy truck (50 feet)	90	Very annoying Hearing damage (8-hour, continuous exposure)
Pneumatic drill (50 feet)	80	Annoying
Freight train (50 feet) Freeway traffic (50 feet)	70 to 80	
	70	Intrusive (Telephone use difficult)
Air conditioning unit (20 feet)	60	
Light auto traffic (50 feet)	50	Quiet
Living room Bedroom	40	
Library Soft whisper (5 feet)	30	Very quiet
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

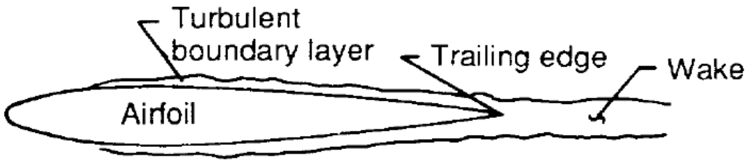
Wind turbine sound originates from either a mechanical or aerodynamic generation mechanism. Mechanical sound originates from the gearbox and control mechanisms. Standard noise control techniques typically are used to reduce mechanical sound. Mechanical noise is not typically the dominant source of noise 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.

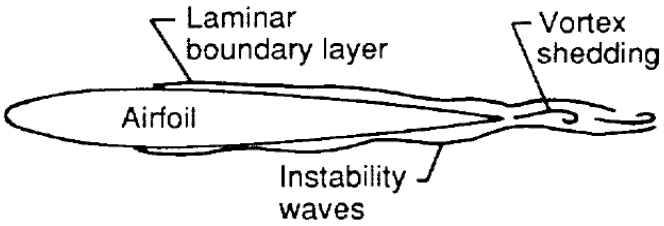
Aerodynamic sound is produced by the rotation of the turbine blades through the air. A turbine blade shape is that of an airfoil. An airfoil is simply a structure with a shape that produces a lift force when air passes over it. Originally developed for aircraft, airfoil shapes have been adapted to provide 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



Turbulent-boundary-layer—trailing-edge noise



Laminar-boundary-layer—vortex-shedding noise

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.

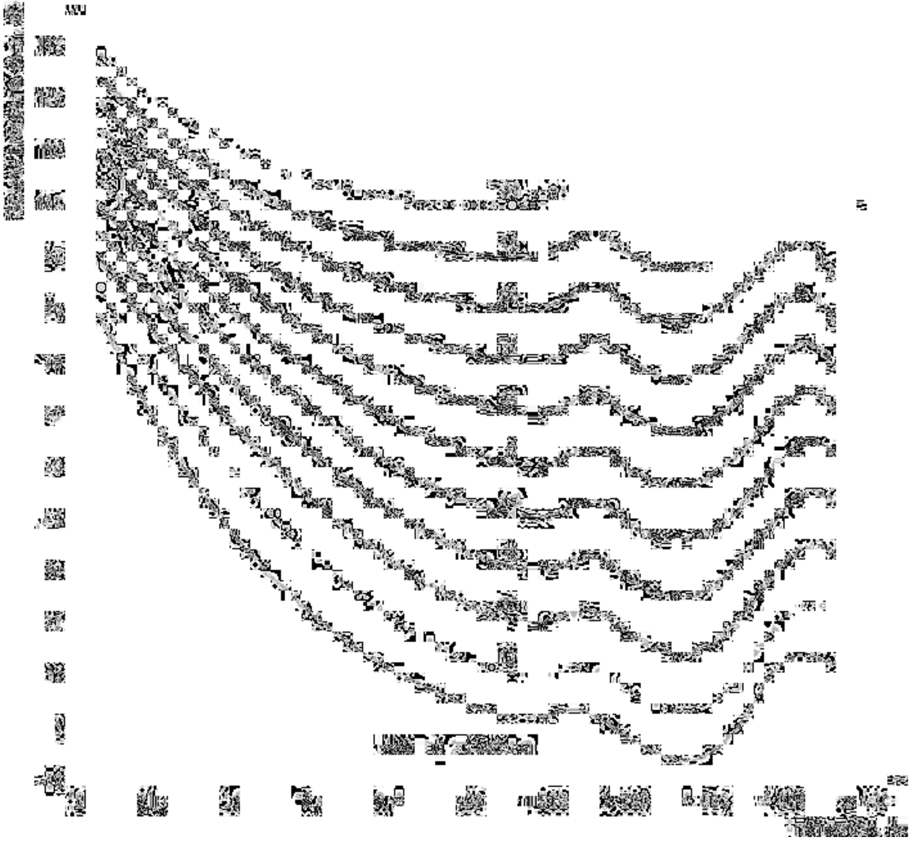
Table 3-2 also shows that even sounds as low as 4 Hz can be heard if the levels are high enough (107 dB). However, levels from wind turbines at 4 Hz are more likely to be around 70 dB or lower, and therefore inaudible. Studies conducted to assess wind turbine noise have shown that wind turbine sound 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).

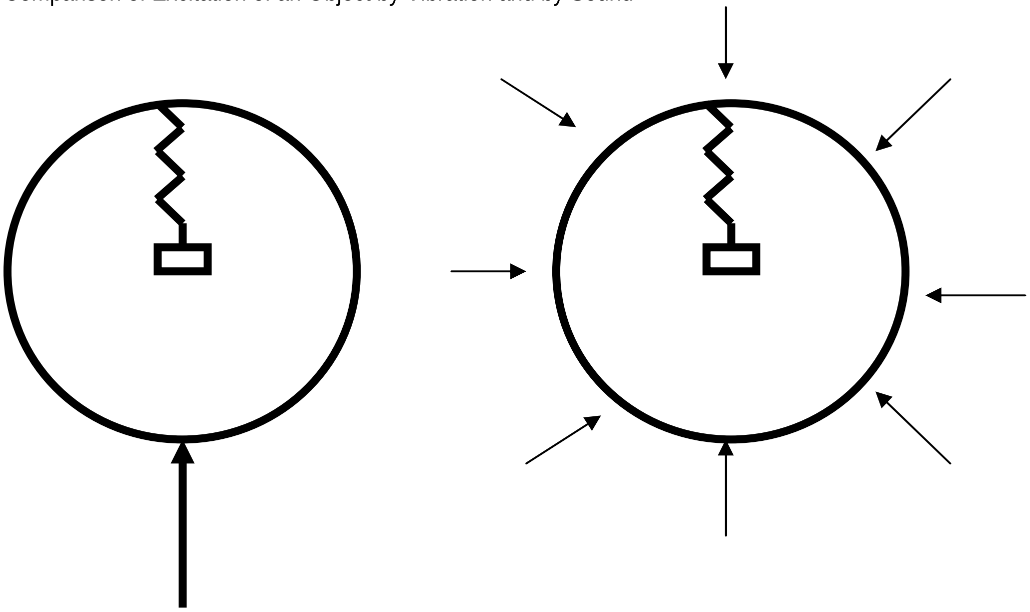
As higher frequency vibrations attenuate rapidly, it is low frequencies which are of potential concern to human health. When vibration is detected through the feet or through the seat, the focus of interest is the vibration of the surface with which one is in contact—for example, when travelling in a 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[1] 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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[1] 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[2] (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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[2] 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^2.

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^2, 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^2).

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 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).

SECTION 4

Results

This section discusses the results of the anaylsis 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.[3] 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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[3] 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[4] 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.[5]

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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[4] 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.

[5] 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 to) 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

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.

SECTION 5

Conclusions

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

APPENDIX A

Fundamentals of Sound

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 (N/m^2), and a sound pressure of 94 dB re 20µPa 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, λ
- Velocity, c = 340m/s approx, depending on temperature

The velocity and wavelength are related by: velocity = wavelength x 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 N/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:

$\log_{10}10 = 1$
$\log_{10}100 = 2$
$\log_{10}1000 = 3$

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 (μPa) ($2\text{x}10^{-5}$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.

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

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

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

Sound pressure level, $L_P = L_w - 20\log[r] - 11$ 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 (Leq): 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 LAeq, 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 L90 and L10. The L90 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

APPENDIX B

The Human Ear

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

APPENDIX C

Measuring Sound

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.

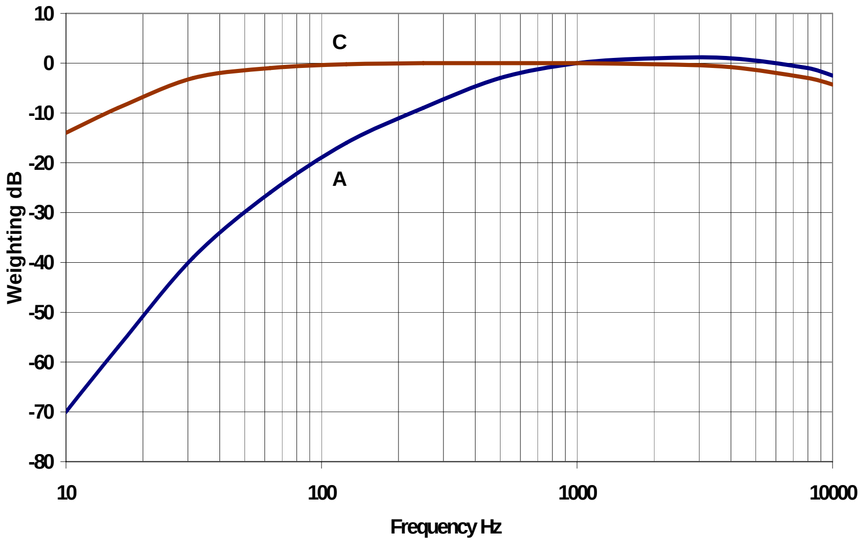
The weighting network and electrical filters are an important part of the sound level meter, as they give an indication of the frequency components of the sound. The filters are as follows:

- 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

APPENDIX D

Propagation of Sound

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

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

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

APPENDIX E

Expert Panel Members

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.

Dr. David M. Lipscomb received a Ph. D. in Hearing Science from the University of Washington (Seattle) in 1966. Dr. Lipscomb taught at the University of Tennessee for more than two decades in the Department of Audiology and Speech Pathology. While he was on the faculty, Dr. Lipscomb developed and directed the department's Noise Research Laboratory. During his tenure at Tennessee and after he moved to the Pacific Northwest in 1988, Dr. Lipscomb has served as a consultant to many entities including communities, governmental agencies, industries, and legal organizations.

Dr. Lipscomb has qualified in courts of law as an expert in Audiology since 1966. Currently, he investigates incidents to determine whether an acoustical warning signal provided warning to individuals in harms way, and, if so, at how many seconds before an incident. With his background in clinical and research audiology, he undertakes the evaluation of hearing impairment claims for industrial settings and product liability.

Dr. Lipscomb was a bioacoustical consultant to the U. S. Environmental Protection Agency Office of Noise Abatement and Control (ONAC) at the time the agency was responding to Congressional mandates contained in the Noise Control Act of 1972. He was one of the original authors of the Criteria Document produced by ONAC, and he served as a reviewer for the ONAC document titled *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety*. Dr. Lipscomb's experience in writing and reviewing bioacoustical documentation has been particularly useful in his review of materials for AWEA regarding wind farm noise concerns.

Robert J. McCunney, M.D.

Robert J. McCunney, M.D., M.P.H., M.S., is board certified by the American Board of Preventive Medicine as a specialist in occupational and environmental medicine. Dr. McCunney is a staff physician at Massachusetts General Hospital's pulmonary division, where he evaluates and treats occupational and environmental illnesses, including lung disorders ranging from asbestosis to asthma to mold related health concerns, among others. He is also a clinical faculty member of Harvard Medical School and a research scientist at the Massachusetts Institute of Technology Department of Biological Engineering, where he participates in epidemiological research pertaining to occupational and environmental health hazards.

Dr. McCunney received his B.S. in chemical engineering from Drexel University, his M.S. in environmental health from the University of Minnesota, his M.D. from the Thomas Jefferson University Medical School and his M.P.H. from the Harvard School of Public Health. He completed training in internal medicine at Northwestern University Medical Center in Chicago. Dr. McCunney is past president of the American College of Occupational and Environmental Medicine (ACOEM) and an accomplished author. He has edited numerous occupational and environmental medicine textbooks and over 80 published articles and book chapters. He is the Editor of all three editions of the text book, *A Practical Approach to Occupational and Environmental Medicine*, the most recent edition of which was published in 2003. Dr. McCunney received the Health Achievement Award from ACOEM in 2004.

Dr. McCunney has extensive experience in evaluating the effects of noise on hearing via reviewing audiometric tests. He has written book chapters on the topic and regularly lectures at the Harvard School of Public Health on "Noise and Health."

Michael T. Seilo, Ph.D.

Dr. Michael T. Seilo received his Ph.D. in Audiology from Ohio University in 1970. He is currently a professor of audiology in the Department of Communication Sciences and Disorders at Western Washington University in Bellingham, Washington where he served as department chair for a total of more than twenty years. Dr. Seilo is clinically certified by the American Speech-Language-Hearing Association (ASHA) in both audiology and speech-language pathology and is a long-time member of ASHA, the American Academy of Audiology, and the Washington Speech and Hearing Association.

For many years Dr. Seilo has taught courses in hearing conservation at both the graduate and undergraduate level. His special interest areas include speech perception and the impact of noise on human hearing sensitivity including tinnitus.

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.

Bo Søndergaard, M.Sc. (Physics)

Bo Søndergaard has more than 20 years of experience in consultancy in environmental noise measurements, predictions and assessment. The last 15 years with an emphasis on wind turbine noise. Mr. Søndergaard is the convenor of the MT11 work group under IEC TC88 working with revision of the measurement standard for wind turbines IEC 61400-11. He has also worked as project manager for the following research projects: Low Frequency Noise from Large Wind Turbines for the Danish Energy Authority, Noise and Energy optimization of Wind Farms, and Noise from Wind Turbines in Wake for Energinet.dk.

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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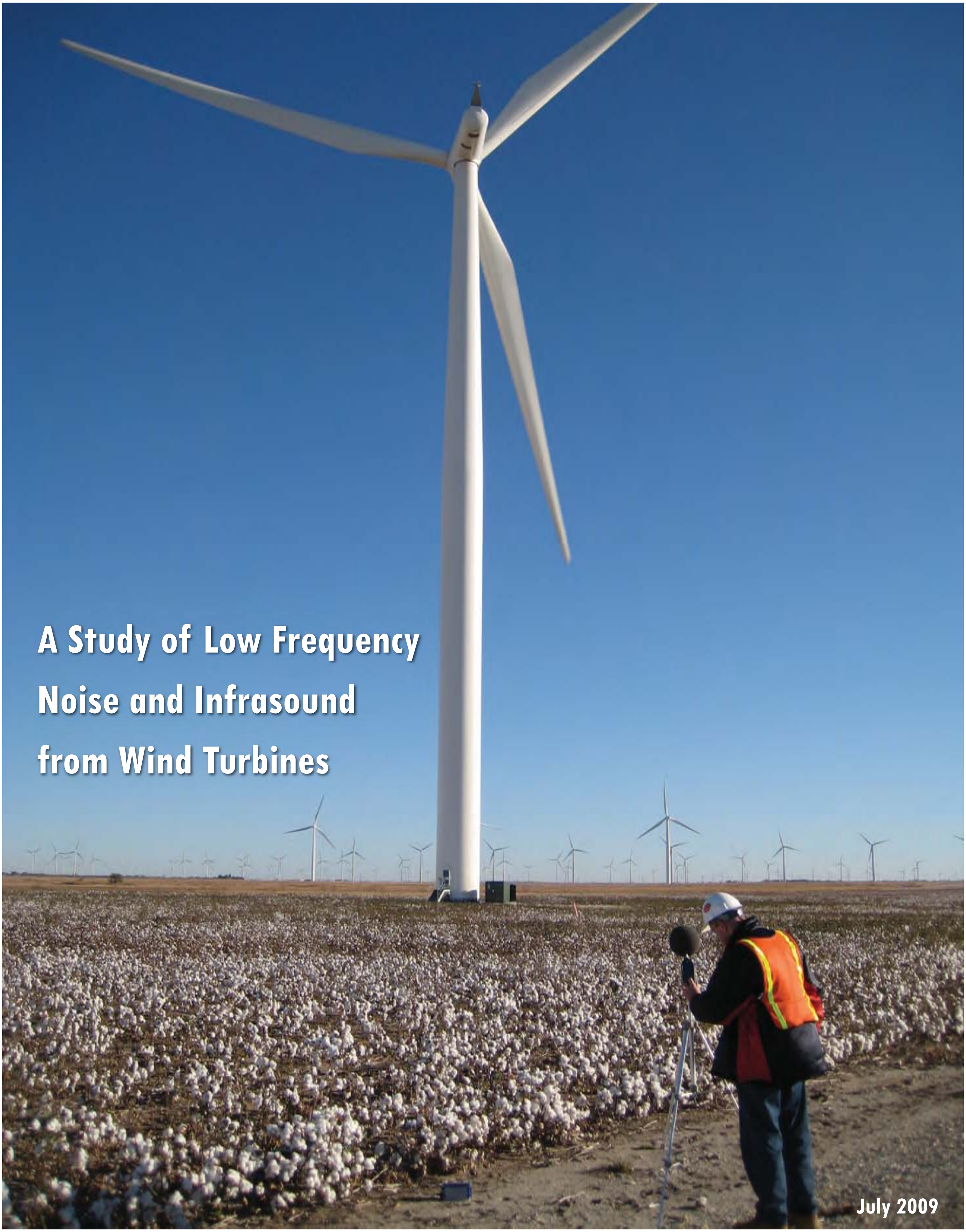
A Study of Low Frequency Noise and Infrasound from Wind Turbines



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July 2009

Report No. 2433-01

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ES EXECUTIVE SUMMARY

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

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".