ABSTRACT

Title of Document: INTEGRATED ENERGY AND ENVIRONMENTAL ANALYSIS OF UTILITY-SCALE WIND POWER PRODUCTION

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Climate change associated with industrial activity threatens environmental and economic systems worldwide. Wind power was presented as one of several technologies that collectively could mitigate many of the adverse effects of global climate change if deployed at sufficient scale. The objective of this study was to explore the sustainability implications of deploying wind at that scale. The Maple Ridge Wind Energy Facility was identified as the target for analysis. Emergy analysis was performed to explore the total environmental and economic impact of the facility in common units; Energy Return on Energy Investment (EROI) was quantified to explore the net energy yield of the facility. EROI and emergy analyses suggested that Maple Ridge is a sustainable enterprise with moderate environmental impact relative to other electricity generation facilities. Implications of these results on the energy landscape of the future were discussed. Policy options to facilitate wind energy industrial growth were explored.

INTEGRATED ENERGY AND ENVIRONMENTAL ANALYSIS OF UTILITY-SCALE WIND POWER PRODUCTION

by

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The tower-like mill
High on the hill,
Tells us of many fair homesteads concealed
In the valleys around;
Where wavering in the sunlight, many a field
Of bright grain may be found.

The wild free wind
They have sought to bind
And make it labor like all other things
Nought careth he;
Joyfully he works, while joyfully sings,
And wanders free.

-Caroline Tappan
Excerpt from the poem Windmill
1891

The last ton of coal can be quarried; the last gallon of oil can be sucked up from the ground—but while there is air and varying temperatures, the wind must whirl and sweep over the globe. It is strange that this free and universal source of power is but little used by us. It will work for you all day and all night and it is very easily utilized.

-New York Times editorial
December 14, 1919

Faith in the redemptive power of wind energy is not a substitute for analysis of its actual record.

-Eric Rosenbloom
Author and outspoken opponent of wind energy development in Vermont
2006

Table of Contents

List of Tables

List of Figures

CHAPTER 1. PROBLEM STATEMENT

Wind and the climate problem

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) quantifies anthropogenic impacts to the climate. The assessment states that the global atmospheric concentration of carbon dioxide has increased from pre-industrial levels of about 280 ppm to 379 in 2005. The annual carbon dioxide concentration growth rate was larger in the ten years ending 2005 then at any time since direct measurement of carbon dioxide concentration began. The primary source of the increased atmospheric concentration of carbon dioxide results from the combustion of fossil fuels; land use change has played an ancillary role. The atmospheric concentrations of greenhouse gasses like methane and CO2 is now greatly exceed their natural ranges over the last 650,000 years. These gases, working in concert with nitrous oxide and a few others, exert a radiative force of about 2.3 W/m^2. This force is generating a warming trend. The IPCC forecasts a warming of more than 0.2 degrees C per decade under likely emissions scenarios (IPCC, 2007).

Warming is expected to be greatest over land and at northern latitudes where snow cover is expected to contract. As a result of decreased snow cover, albedo may decline exacerbating the warming trend. Permafrost may melt leading to the decay of vegetation and methane liberation. Sea ice is expected to melt and sea levels are expected to rise. Warmer ocean waters will expand exacerbating the sea level issue (IPCC, 2007)). Widespread destruction of coral reefs, wetlands, and coastal habitats are anticipated. Typhoons and hurricanes may become more intense. Heat waves and heavy precipitation events will become more frequent (Environmental Defense, 2002). Precipitation patterns may change. Cold-adapted species may retreat to the poles and tropical species may proliferate. In the lexicon of the IPCC assessment, these calamitous phenomena are between “likely” and “virtually certain,” (IPCC, 2007) .

Pacala and Socolow (2004) proposed in a seminal paper that humanity already possesses the tools necessary to mitigate many of these adverse effects. By scaling up proven technologies, the authors proposed that humanity could stabilize green house gas concentrations at less than a doubling of pre-industrial levels by the middle of this century. The authors identified a portfolio of fifteen “stabilization wedges” which, if employed collectively, could accomplish this goal.

Some stabilization wedges would have significant disadvantages. For example, adding 700 GW of nuclear capacity would incur significant financial cost and raise the specters of proliferation, waste disposal, and cataclysmic accidents. Costly research and development would be required to introduce carbon capture and sequestration to 800 GW of coal-fired baseload capacity (Riahi, 2004). Increasing global biofuels production by a factor of 50 would require the appropriation of one-sixth of the world’s arable land (Pacala and Socolow, 2004).

Other wedges would be easier to realize. Technological innovation leading to efficiency and conservation could avoid hundreds of GtC emissions. Proactive forest management, reforestation, and afforestation may be able to sequester 25 GtC over 50 years. Wind power is also among the low-hanging fruit. The authors propose that 2,000 GW of wind power - 50 times today's global deployment - could avoid 50 GtC emissions by mid-century (Pacala and Socolow, 2004).

Although several of the wedges propose alternative power generation strategies, wind is most attractive for several reasons. Although the photovoltaic industry has made strides, PV power has yet to prove itself as a scaleable alternative. Increasing photovoltaic power production 700 fold as prescribed by Pacala and Socolow (2004) may not be possible (National Center for Photovoltaics, 2005). Natural gas is an attractive low-carbon fossil fuel, bit it has many competing uses, e.g., as a feedstock for fertilizer, plastic production, and industrial chemicals. Nuclear energy is attractive from a life-cycle green house gas perspective, but has profound proliferation, waste generation, and safety concerns. Wind power is derived from an abundant, renewable resource. The conversion of the wind into electricity is a mature, scalable technology with a small environmental footprint. Barring a global capitulation to climate change, wind turbines will become a significant feature of the energy landscape of the future.

The evolution of wind power into a mature technology

Wind is formed by the differential heating of the earth's surface. Globally, warm air at the equator rises and rushes toward the poles creating a pressure differential. High-pressure polar air sinks and rushes toward the equator. These cells drive the trade winds and promote atmospheric circulation. Locally, wind may be abundant on sites free of obstacles such as open water and desert environments. Wind speed and direction tends to vary diurnally and seasonally (Bonan, 2005).

Appropriation of energy from wind for human use dates to antiquity. Forty thousand years ago, South East Asians may have used primitive sailing craft to reach Australia. Much later (1500 BC), their descendants employed sophisticated sailing canoes to explore and colonize the islands of Polynesia (Diamond, 2005). Simple vertical axis frame-and-sail windmills were developed to automate grain grinding in sixth century Persia. Comparable machines are still in use in Central Asia (Hills, 1996).

Horizontal axis turbines were developed independently in Europe during the 12^{th} century. Vertical waterwheels provided the parent technology for early European wind turbines. The vertical axle and the gearing from waterwheels were adopted in the earliest designs. Early wind turbines were employed to mill grain into flour. They featured the ability to yaw into the wind to maximize energy conversion. Wind energy may have provided 25% of Europe's industrial energy from the fourteenth century to the industrial revolution (Righter, 1996).

Windmills debuted in North America in the mid-nineteenth century. More than six million mechanical output windmills were operating in the Great Plains between 1880 and 1930. Wind electric generators arrived in the late 19th century. Charles Brush built a 40 ton, 30 m tall, 12kW machine in 1887 that achieved high availability for more than 20 years. Comparable machines were developed in Denmark and Scotland concurrently. Small wind electric generators proliferated in regions of the American west not yet connected to the grid. However, by the mid-20th century, the Rural Electrification Administration had brought the electricity grid to much of rural America. The nascent wind industry atrophied for several decades at home and abroad (Righter, 1996).

American research and development efforts thereafter were geared toward MW-scale turbines with grid connectivity. A16-ton, two-bladed machine with a 60m stainless steel rotor oriented downwind of the tower was installed in Vermont in 1941, though it failed catastrophically after several hundred hours of intermittent operation (Hills, 1996). The Danish built smaller machines that achieved high availability and incurred few maintenance costs. For example, the Gedser 200kW turbine operated from 1957 to 1967. Modern turbines share many features with the Gedser including a three bladed upwind design and the ability to yaw into the wind (Danish Wind Industry Association, 2003c)

During the 1970s, federal research and development in the United States led to the design, fabrication, and testing of several notable MW-scale machines. For example, the 2 MW MOD-1 machine was built in North Carolina in 1980. It featured a two-bladed rotor oriented downwind of the tower. The dynamic loads generated by the dead zone behind the tower proved too much for the steel blades to bear. Rotor fatigue scuttled the prototype after a few months of intermittent operation (Righter, 1996). The 2.5 MW

MOD-2 machine also featured a two-blade, downwind rotor. This design featured a teetering hub to relieve the stress associated with dynamic loads. However, the 100-meter diameter steel rotor fatigued more quickly than anticipated and the experiment failed. The domestic private sector in the United States also failed to produce reliable machines capable of producing low-cost electricity (Righter, 1996).

California experienced a wind rush in the early 1980s due to a suite of generous tax incentives. Thousands of turbines were erected at Altamont, Tehachapi, and San Gorgino Passes; some machines lasted hours while others are still in service. Many of the successful designs had common characteristics including a three blade upwind design, a yaw mechanism enabling the rotor to turn into the wind, and a capacity of 500 kW or less. Successful manufacturers included Vestas, Bonus, and Micon. The rush ended abruptly in 1985 when tax incentives were rescinded (Righter, 1996). The struggling domestic wind industry collapsed and the global industry entered a period of mergers and reorganization (Danish Wind Industry Association, 2003b).

Manufacturers in Denmark and elsewhere set about slowly scaling up the designs that had worked well at kW scale. Many innovations were realized in this period. Vestas developed blade pitch regulation technology capable of managing the quantity of electricity delivered to the grid and protecting the machines from overspeed damage. They reduced blade weight by two-thirds enabling taller towers and larger swept rotor areas. Sales throughout the industry increased as Germany, Denmark, and Spain emerged as leading markets Power production capacity of state of the art machines crept up steadily. By the late 1990s, MW-scale machines arrayed in wind farms had become the norm for utility-scale generation of electricity from wind (Danish Wind Industry Association, 2003a).

Policy drivers in the United States reopened the domestic market to wind development in the 1990s. The Production Tax Credit (PTC), first enacted in the early 1990s, provided an incentive for renewable developers to generate power and deliver it to the grid. The PTC has been in effect intermittently since 1992 and now offers reduced income tax liability of $0.019/kWh for qualifying energy sources.[1] Renewable portfolio standards (RPSs) proliferated among states beginning in the late 1990s. These legislation mandated that a certain portion of a given state's electricity portfolio be met by a qualifying renewable energy resource by a future date. Chen (2008) discussed the impact RPSs have had on the renewable energy landscape and role they will play moving forward.

Global installed wind capacity has grown from less than 5 GW in 1995 to more than 74 in 2006. Germany and Spain are the leading markets; the US is close behind. The US leads all nations in wind capacity growth. Installed capacity of wind projects in the United States grew from 2 GW in 1997 to more than 12 GW in 2006 (Global Wind Energy Council, 2006). During a speech in Milwaukee in early 2006, President Bush stated that he "recogniz(ed) the importance of wind power. About 6% of the continental US has been identified as highly suitable for the construction of wind turbines. Some have estimated that this area alone has the potential to supply 20% of our nation's

[1] *For more information about Production Tax Credit, refer to North Carolina State University, 2008.*

electricity," (Bush, 2006). The US Department of Energy Office of Energy Efficiency and Renewable Energy (DOE/EERE) recently published a report suggesting 20% penetration of wind generation would be feasible by 2030 provided environmental impacts are mitigated, manufacturing capacity is ramped up, and transmission constraints are resolved (DOE/EERE, 2008). Wind generates less than 1% of domestic electricity generation capacity today (Tester, 2005).

The sustainability of wind power is unknown

Wind energy is poised to contribute significantly to the renewable energy future. However, the words 'renewable' and 'sustainable' are not synonymous. Some renewable energy technologies are not sustainable. For example, scholarship suggests that making ethanol from corn has a low energy yield per unit energy input and that production processes rely on non-renewable resources such as coal, natural gas, and oil. Thus, despite the renewable feedstock, these ethanol products may be no more sustainable than the non-renewable fuels on which they depend.[2]

Wind turbines are comprised of several components. Each of these incurs an energy cost and environmental impact. The tower and support structures are made of steel and

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2 *There is debate about the sustainability of biofuels. Regarding corn-based ethanol for example, Pimentel (2003) contends that it has a low net energy yield. However, Farrell (2006) argues it has a positive net energy yield and "can contribute to energy and environmental goals."*

may be taller than 100 m.[3] The tower sits on a foundation typically comprised of steel reinforced concrete. The nacelle features a generator, gear system, main shaft, yaw system, flanges, and other components. Each of these components must be manufactured from primary materials, transported to the site, and assembled into turbines that must be connected to the grid and maintained over the project life cycle by highly trained operation and maintenance personnel.

Global installed capacity of wind is projected to grow at 19.1% through the end of this decade (Global Wind Energy Collaborative, 2006, p.7). Given the scale to which wind power is anticipated to grow, it's appropriate to evaluate the technology's sustainability. In this study, energy return on investment (EROI) is calculated and emergy analysis is performed to explore the sustainability of wind and quantify the dependence of the technology on non-renewable resources.

EROI offers one sustainability metric

The first studies to explore the life cycle energy consumption of industrial goods and services date to the late 1960s. For example, in 1969, the Coca Cola Company compared resource consumption associated with different types of beverage containers (Bullard, 1978; European Environment Agency, 1999). Throughout the energy crises of the 1970, studies such as Coca Cola's were principally designed to identify energy flows within a

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[3] *See General Electric, 2006 for a discussion of the GE 3.6 MW turbine. The rotor diameter on the machines are more than 100m. The hub height is determined based on unique site characteristics.*

system and introduce efficiency where practicable. A suite of tools evolved to help analysts explore the energy impacts of industrial processes (Bullard, 1978; Boustead, 1979; International Federation of Institutes for Advanced Studies, 1978; Oak Ridge, 1977). During the mid 1980s, this suite of tools evolved into Life Cycle Assessment (LCA). LCA typically involves the examination of all environmental aspects of a product system through its life cycle (European Environmental Agency, 1999). LCA shares a common ancestor with Six Sigma, a statistical tool developed by Motorola and General Electric to analyze industrial process, reduce variation, and guide organizational improvement. Although holistic life cycle tools such as LCA and Six Sigma are now widely used, single criterion approaches are still employed. A common application of the single criterion approach is Energy Return on Invested (EROI).

EROI is "the quantity of energy delivered to society by an energy system to the energy used directly and indirectly in the delivery process" (Cleveland, 2005). Allied terms include energy surplus, energy balance, and net energy analysis. EROI quantifies the efficiency and effectiveness of energy capture in a system. It has been characterized as the central organizing principle in ecology and the motive force behind natural selection by seminal biologists Alfred Lotka and Howard Odum. They believed that selective advantage accrued to organisms capable of efficiently channeling available energy into preservation and proliferation (Cleveland, 2007). Tainter (2003 and 1990) and Diamond (2005) have explored the prosperity of societies with access to high net energy resources and the role of resource exhaustion in societal collapse.

Energy is lost in all conversion processes in accordance with the second law of thermodynamics. Therefore, high EROI is essential for primary energy production systems such as electric power plants. Due to this phenomenon, power production has been an active area of EROI research. Many of these studies concern renewable energy technologies and/or the transition to a renewable energy future. Some feature data regarding energy return as part of a more inclusive LCA while some are single criterion energy analyses (e.g., Cleveland, 2005; Cleveland and Herendeen, 1989; Pehnt, 2006; Sorensen, 1994; Kahn, 2005).

Lenzen (2002) compiled twenty-five energy return studies that either concerned wind energy exclusively or addressed wind and other technologies. The compiled studies were performed between 1981 and 2001. The turbines under study varied in capacity from several kWs to 6.6 MW. Some studies were based on data collected in the field while others were conceptual. There were methodological differences between the studies.

This study will employ EROI analysis techniques developed by Bullard (1978). Many EROI analyses have been conducted using Bullard's methodology (e.g., Cleveland, 2005), so this will facilitate a comparison of Maple Ridge to other wind energy facilities and other energy generation technologies.

Emergy indices are also sustainability metrics

Emergy techniques also evolved during the energy crises of the 1970s. These techniques analyze flows of energy and other resources through a system as they converge to produce an output. Emergy techniques recognize that solar energy, deep earth heat, and tidal energy are the three primary sources of energy for the earth's ecosystems and that all natural and economic goods and services have embodied within them these primary energy sources. Solar energy – the solar embodied joule (sej) - is the basic unit of energy equivalence in the emergy paradigm (Odum, 1996). Emergy values allow the analyst to evaluate the relative position of goods and services in the thermodynamic hierarchy of the biosphere. For example, freshwater has 18,000 times as much embodied solar energy as incident solar radiation because freshwater required dissipation of solar energy over land and sea for its generation and delivery to an ecosystem (Felix, 2007). Emergy analysis thereby facilitates the comparison of diverse economic and ecological goods and services in common units.

Indices and ratios based on emergy flows through a system can be used to analyze system behavior. For example, the emergy yield ratio (EYR) is defined as the ratio of the total local and imported emergy driving a system to the emergy exported from the system. The EYR can illustrate a system's potential to either contribute to a local economy or become reliant upon it (Ulgiati, 1995).

Several studies have developed emergy yield ratios for wind energy (e.g., Odum 1976; Brown and Ulgiati, 2002), but none have examined modern turbines. The study by Brown and Ulgiati (2002) examined a wind farm featuring five 500 kW machines constructed for the municipality of Bologna, Italy by Riva Calzoni in 1996. Several other types of energy generation systems have been examined using emergy techniques (e.g., Odum, 2000; Brown and Ulgiati, 2002; Carraretto, 2004; Wang, 2005). This study will employ emergy techniques to develop indices for the Maple Ridge Wind Energy Facility (see following section). These indices will be compared to indices for other types of electricity generation technology in order to gauge the sustainability of the technology relative to other electric power generation technologies.

Maple Ridge Wind Energy Facility will be the target system

Maple Ridge Wind Energy Facility near Lowville, New York will serve as the target system for both the EROI and emergy analyses. Maple Ridge features 195 Vestas V82 1.65 MW turbines. Each turbine is about 80 m tall and features a swept rotor area of 5,281 m2 (Vestas, 2007). Maple Ridge is the largest wind energy facility in New York State and among the largest in the world. If Pacala and Socolow's (2004) vision of 2,000 GW of wind power by 2050 is realized, many developments like Maple Ridge will need to be constructed between now and then.

Lenzen's meta-analysis of several wind EROI studies (2002) suggests that wind energy technologies offer a generally favorable energy return. The few EYR analyses that have been performed on wind (Odum 1976; Brown and Ulgiati, 2002) also suggest that the technology is sustainable. Therefore, it is hypothesized that an evaluation of Maple Ridge Wind Energy Facility will suggest the facility is sustainable relative to other electricity generation technologies.

CHAPTER 2. METHODOLOGY

This chapter presents methods to develop indices of sustainability for utility scale wind energy. First, the manufactured, natural, capital, and temporal boundaries of the system are defined. Second, a protocol for describing the system in a diagram using systems language will be developed. Third, EROI analysis is presented as a step-by-step procedure. Fourth, emergy analysis is presented as a step-by-step procedure. Finally, sustainability indices are defined and explained.

System Boundaries

Manufactured contributions

This thesis employs sustainability metrics to characterize Maple Ridge Wind Energy Facility. Maple Ridge is comprised of 195 Vestas V-82 wind turbines and associated transmission infrastructure. Resource inputs associated with four wind farm life cycle stages were explored: 1) Manufacturing of wind turbine components, 2) Transport of turbine components to the site, 3) Operation and Maintenance, and 4) Decommissioning.

Manufacturing of wind turbine components

This life cycle stage includes the manufacturing of wind turbine components from raw or value added materials. Components of the Maple Ridge Wind Energy Facility include turbine foundations, towers, nacelles, rotors (including blades, hubs, and nacelle connections), cables, and a substation.

Transport of turbine components to the construction site and erection

Although significant energy is consumed in the course of transporting the components of the Maple Ridge Wind Energy Facility from the factory floor to the construction site, the capital cost of these energy expenditures is included in the capital cost of the facility. To avoid double counting, the transport of turbines and components to the construction site will only be included in the capital cost under the services section of the analysis.

Operation and maintenance

This stage includes labor associated with operation and maintenance activities. Materials such as lubrication are also included. In accordance with the manufacturer's projections (Vestas, 2006), it is assumed that the gearbox within the nacelle will be replaced once within the project life cycle.

Decommissioning

This stage includes crane and rigging labor associated with decommissioning activities.

Natural Contribution

Wind

Other emergy analyses of wind facilities have employed as an input the total kinetic energy incident on the tower (e.g., Brown and Ulgiati, 2002). Only a small portion of this energy is engaged in propelling the rotor of the turbine, so this technique may overstate the role on wind in the system. Only the wind incident upon and available to the rotors of the turbines at Maple Ridge was included as an energy input to the Maple Ridge Wind Energy facility.

Topographical models suggest that the area around Maple Ridge is characterized by class three wind resource (AWS TrueWind, 2007). The American Wind Energy Association describes class 3 wind resource as characterized by average wind speeds of 6.7 m/s at a height of 50 m (AWEA, 2007). The hub height of the turbines at Maple Ridge is 82 m. Energy in the wind incident on the rotors of the Maple Ridge turbines was calculated using these data. Natural contributions are excluded from EROI analyses in accordance with Bullard's methodology.

Land appropriation

Land must be appropriated for turbine construction. At the Maple Ridge Wind Energy Facility, most of the turbines are located on agricultural land, so this land is taken out of production to support turbine operation. Opportunity costs associated with lost production will be incorporated into the emergy analysis. Bullard's methodology does not facilitate the computation of such costs, so including these opportunity costs would be beyond the scope of an EROI analysis.

Wildlife Impacts

Wind turbines exact an impact on certain wildlife populations. Adverse impacts to bird and bat populations will be denoted in the emergy analysis as energetic drains from the system. Including these energetic drains would be beyond the scope of an EROI analysis. Furthermore, Bullard's methodology does not facilitate the computation of such phenomena.

Capital Contribution

The capital cost of the Maple Ridge Wind Energy Facility was $350 million dollars. This figure includes capital expenditures associated with the procurement of the facility's components and the labor and fuel costs associated with the delivery of the components to the construction site. Construction costs are also included (D'Estries, 2006). This figure was included in the EROI and emergy analyses.

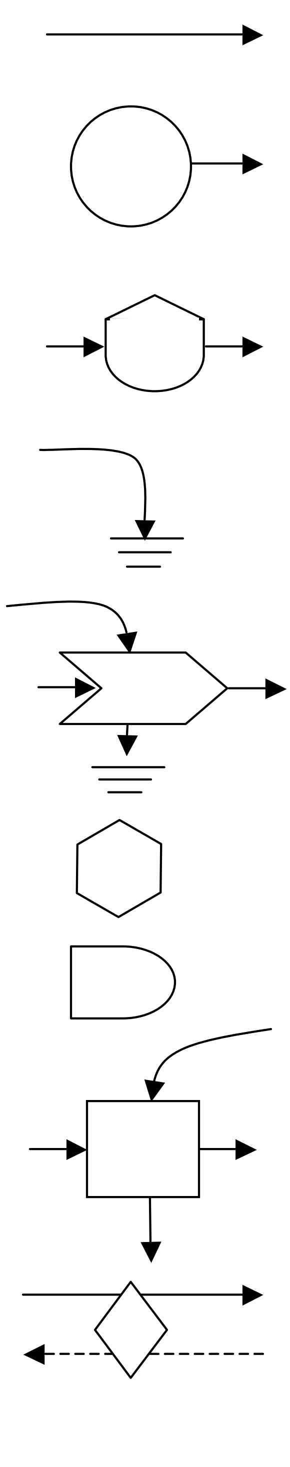
Temporal System Boundaries

In accordance with the manufacturer's projections, project life cycle is expected to be 20 years (Vestas, 2006). This may be a conservative estimate. Many Vestas machines manufactured in the early 1980s are still operating in the sprawling Altamont Pass, Tehachapi Pass, and San Gorgino Pass wind developments in California.

Using Systems Language to Describe the Maple Ridge Wind Energy Facility

The purpose of the systems diagram is to conduct an inventory of the processes, storages, and flows of energy in the system (Brown and Ulgiati, 2004). Systems diagrams may be read from left to right where low entropy energy system components are arranged on the left and successively higher entropy components are on the right. A language has been developed to describe energy flows within systems. This language is summarized in Figure 1.

A diagram of the Maple Ridge Wind Energy Facility will be developed in accordance with Odum's language (Odum, 1996). The diagram will illustrate natural and economic contributions to the system, energy flows within the system, and exchanges between the wind facility and the economy. A summary of the life cycle of the wind farm will accompany the diagram.



Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.

Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.

Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.

Consumer. Unit that transforms energy quality, stores it, and feeds it back auto-catalytically to improve inflow.

Producer. Unit that collects and transforms low-quality energy under control interactions of high quality flows.

Box. Miscellaneous symbol to use for whatever unit or function is labeled.

Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 1. Energy systems language symbols

EROI Analysis Methodology

Bullard (1978) developed techniques for quantifying the EROI of industrial processes. In his *Handbook for Combining Process and Input-Output Analysis*, Bullard analyzed the energy cost of a large prototype coal-fired power plant and offered instructions for analyzing other types of energy generation technologies. Perry (Oak Ridge Associated Universities, Institute for Energy Analysis, 1977) later adapted the technique for other types of systems, but Bullard's technique is presented in this chapter.

Bullard (1978) presented a protocol for fine resolution and course resolution EROI analysis. Fine resolution EROI may be tabulated using hybrid process/input-output analysis, or hybrid analysis. Using this technique, the analyst first itemizes all of the energy and material inputs to the target system (excluding natural energies and labor), and then uses process analysis to determine the energy content of the fuels used in the facility's life cycle. Material inputs are then quantified using input-output analysis. This final step employs a multi-sector model of the US economy featuring data regarding energy use per unit output for each sector, e.g., primary energy associated with the production of $1,000,000 of aluminum or 100 tonnes of porcelain. In 1978, Bullard employed the Standard Industry Classification (SIC) system, a dataset maintained at the time by the Department of Commerce, Bureau of Economic Analysis. This data set featured information regarding the energy intensity of 357 unique economic sectors. Calculation of energy use associated with each component of a target system was therefore a straightforward matter of multiplication (Bullard, 1978). Unfortunately, collection of energy intensity data was discontinued after the energy crises of the 1970s abated and consumer interest in energy issues declined. Neither SIC nor the North American Industry Classification System (NAICS), the dataset that supplanted it, feature energy intensity data, so fine resolution EROI analysis using Bullard's technique is now impossible.

Coarse resolution EROI analysis may be performed by first multiplying the dollar cost of the facility by the average energy intensity for all goods and services in the year of construction. This coefficient is defined as "the ratio of total U.S. energy use to gross national product for the year of construction." The EROI ratio may be obtained by dividing the total projected life-cycle energy generation by the aforementioned product (Bullard, 1978).

Emergy Analysis

Emergy is a measure of available energy that has already been used directly or indirectly in transformations to make a product or service (Odum, 1996). Solar energy is regarded as the primary energy source for all ecological and economic processes. Deep earth heat and tidal energy are other primary energy sources, but these contribute little to earth's ecological and economic processes relative to solar energy. Within the emergy paradigm, natural energy (e.g., wind), fuel energy, energy embodied in goods, energy embodied in services, and energy embodied in production processes may all be expressed in units of the solar energy ultimately required for their creation. These units of solar energy are abbreviated as sej, or solar emjoules. The sej is the basic unit of emergy accounting.

A solar transformity is the solar emergy required to make one joule of energy of a service or product. Transformity is expressed as solar emjoules per joule, or sej/J (Buranakarn, 1998). Transformity characterizes the position of a product or service along the energy hierarchy. By definition, solar energy has a transformity of 1. This indicates that solar energy is diffuse. Wind is derived from solar energy's differential heating of the earth's surface and may therefore be characterized as a concentrated form of solar energy. Odum (1996) has calculated wind's transformity as 1,496 sej/J. One joule of wind energy therefore has an emergy value of 1,496 sej.

For materials, it is sometimes more convenient to express emergy per unit weight, i.e., sej/g. For example, Odum (1996) has calculated the emergy per gram of structural steel as 4.16E11. In this thesis, transformities and emergy per gram values for each input to and output from the Maple Ridge wind energy system will be determined from literature values where available. Otherwise, they'll be calculated.

Brown and Ulgiati (2004) have provided a step-by-step methodology for performing an emergy analysis. First, a table of emergy values must first be prepared. These tables should include information on the flows of materials, labor, and energy. These flows may be obtained from the system diagram. After a table is developed, the emergy of the system can be determined by finding the summation of the unit emergy values. The new unit value may be used to develop indices that may quantify the sustainability of a system.

Using EROI Analysis and Emergy to Develop Sustainability Indices

EROI analysis will yield a ratio of energy invested to energy returned. This ratio will be compared to ratios for other energy generation technologies in order to determine Maple Ridge's position along the EROI spectrum. While energy return studies are capable of identifying energetic 'non-starters', they have limited utility as sustainability indicators.

Emergy values will provide detailed information regarding the position of the wind farm in the thermodynamic hierarchy of the biosphere, but will have limited value in assessing sustainability. To further explore wind's sustainability, several emergy indices will be calculated using methods developed by Odum (1996) and summarized by Brown and Ulgiati (2004 and 1997). The Emergy Yield Ratio (EYR) is defined as the ratio of total emergy driving the target system (Y) to the emergy imported (F). The Environmental Loading Ratio (ELR) is the ration of non-renewable and imported emergy (F+N) to renewable emergy use (R). The Emergy Index of Sustainability is the ratio of EYR to ELR. Emergy index values for Maple Ridge will be compared to values for other energy generation technologies to assess Maple Ridge's – and wind energy's sustainability. Table 1 summarizes the emergy indices that will be explored in this thesis.

Table 1. Emergy Indices

Emergy Index	Formula	Explaination
Emergy Yield Ratio (EYR)	Y/F	The ratio of total emergy driving a system to the emergy exported from the system. This is a measure of the potential contribution of the system to the main economy and a measure of the exploitation of local resources.
Environmental Loading Ratio (ELR)	F+N/R	The ratio of non-renewable and imported emergy use to renewable emergy use. This ratio may be considered a measure of the thermodynamic distance of the system from the natural ecosystem.
Emergy Sustainability Index (EIS)	EYR/ELR	The ratio of the emergy yield ratio to the environmental loading ratio. It measures the potential contribution of a system to the economy per unit of environmental loading.

CHAPTER 3. RESULTS

System Diagram of the Maple Ridge wind Energy Facility

Figure 2 illustrates the main components of the Maple Ridge Energy Facility electricity production system. The diagram provides a generalized view of the sources, flows, interactions, storages, and products associated with the target system. Figure 2 is adapted from Brown and Ulgiati's (2002) diagram of a 2.5 MW wind facility in Italy comprised of ten 250 kW machines.

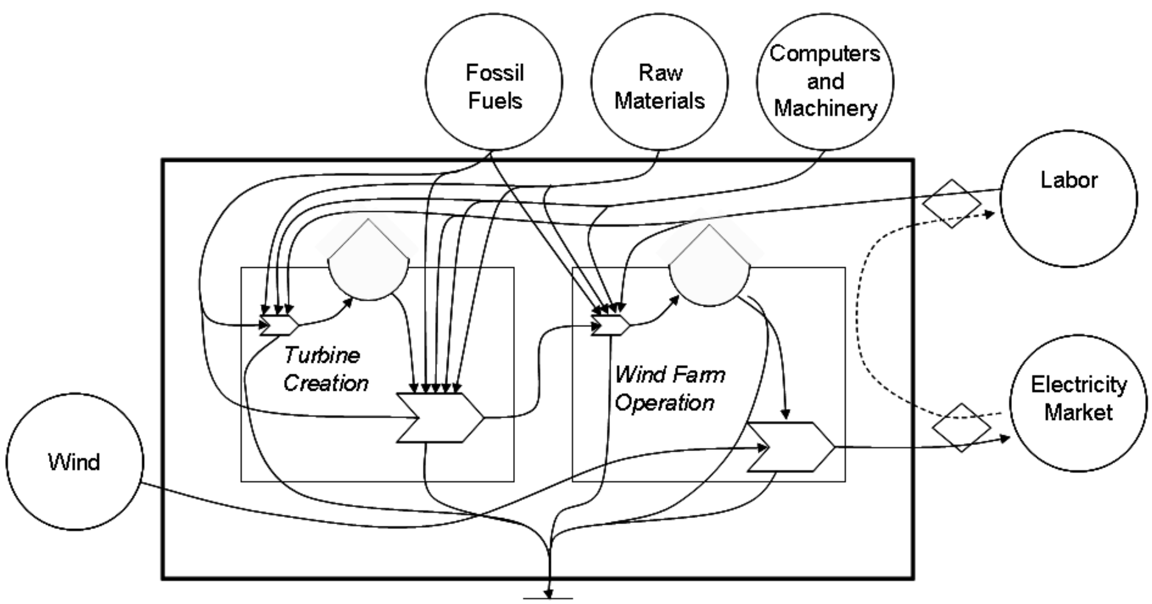


Figure 2. Energy systems diagram of the Maple Ridge Wind Energy Facility

The Maple Ridge Wind Energy Facility is located in Lewis County, New York on the Tug Hill Plateau, an upland region of central New York between Lake Ontario and the Adirondack Mountains. The region is characterized by seasonally heavy snowfall and strong winds. Land use in the vicinity of Maple Ridge is predominantly agricultural.

Horizon Energy and PPM Energy broke ground on the facility in 2005. The project was completed in two phases. Phase one was completed in 2005 and was comprised of 120 Vestas V82 1.65 MW wind turbines; phase two was completed in 2006 and was comprised of 75 V82s. Maple Ridge was connected to the grid in mid 2006. The total power generation capacity of the facility is 321.75 MW. Maple Ridge is the largest wind energy facility east of the Mississippi River.

The V82 is novel machine designed to operate in class 3 wind regimes, i.e., sites that would otherwise be marginal for development. It operates at 14.4 rotations per minute beyond cut-in wind speed and delivers power to the grid at a constant frequency. All turbine functions are computer controlled including blade pitch, rotor yaw, and rotor braking. The Maple Ridge machines each have a rotor diameter of 82 m. The hub height of the Maple Ridge turbines is about 82 m (Vestas, 2007)

Each turbine sits on a 400 m^3 subterranean foundation comprised of more than 800 tons of concrete and 27 tons of steel reinforcement. The 82 m towers are hollow steel cylinders housing transformers and computer equipment. The steel towers comprise more than half of the weight of the turbine. The nacelle sits atop the tower and houses the generator, mechanical brake, gearbox, main shaft, and yaw system. The rotor is bolted to the nacelle and is comprised of three blades. Each blade is about 40 m. The main components of the blade are wood, carbon fiber and fiberglass infused with epoxy resins (Vestas, 2006). The wind turbines are networked via buried cable. Each turbine feeds power to a 230 kV substation. An overhead transmission line delivers electricity 10.3 miles to the Chases Lake Road Interconnection Facility where it joins the grid (Flat Rock Wind, 2004).

Calculation of Inputs to and Outputs from the Maple Ridge Wind Energy System

The following section describes the energetic and material inputs to and outputs from the target system. Assumptions are catalogued. Natural inputs, material inputs and labor are considered separately.

Natural Inputs

Wind

AWS Truewind (2007) indicates that the wind throughout the Maple Ridge Wind Energy Facility is class 3. Wind class describes the wind speed in a column of air; typically, wind speed increases with height. AWEA (2007) described class 3 wind resource as characterized by average wind speeds of about 6.7 m/s at 50 m. The Maple Ridge turbines have a hub height of 82 m. NREL (1986) described the technique whereby wind velocity at a target altitude may be calculated give wind speed at a reference altitude. Application of this technique suggests that average wind speed is about 7.2 m/s at turbine hub height (see Appendix A for calculation). The swept rotor area of each of the Maple Ridge turbines is 5,281m^2 (Vestas, 2007). Therefore, the facility's 195 turbines have a total swept rotor area of 1,029,795 m^2. Energy in wind may be calculated using the following equation.

$$\text{Power} = 0.5(\rho)(A)(v^3)$$

Where ρ = the air density (about 1.225 at sea level)

A = the total rotor area

v = velocity

The Betz Theorm mandates that a maximum of 59.3% of the energy in wind may be appropriated by a turbine (Piggot, 1997), so the total energy in wind was multiplied by this factor to determine the total energy available to the turbine. Using these techniques, it was determined that 2.21 E15 j of wind will be available to the turbines over the project lifecycle. Wind transformity, energy, and emergy calculations are reported in Appendix A.

Wildlife Impacts

Wind turbines exact a toll on bird and bat populations. The Altamont Pass Wind Resource Area, a large facility in central California, earned a reputation in the 1980s as a prolific killer of raptors due to the presence of prey animals in the vicinity and the suitability of first generation, steel lattice turbines as raptor perches. In 2004, a routine mortality study in West Virginia and subsequent statistical analysis determined that between 1,500 and 4,000 bats by the facilities 44 turbines in that year.

Wildlife impacts have emerged as a public relations liability for the wind energy industry. Impacts have motivated community groups in the Mid-Atlantic and elsewhere to mobilize against development in their backyards. Many developers have begun to actively monitor bird and bat impacts in an effort to minimize adverse effects of their facilities, enhance their images among the public, and assuage the concerns of citizens.

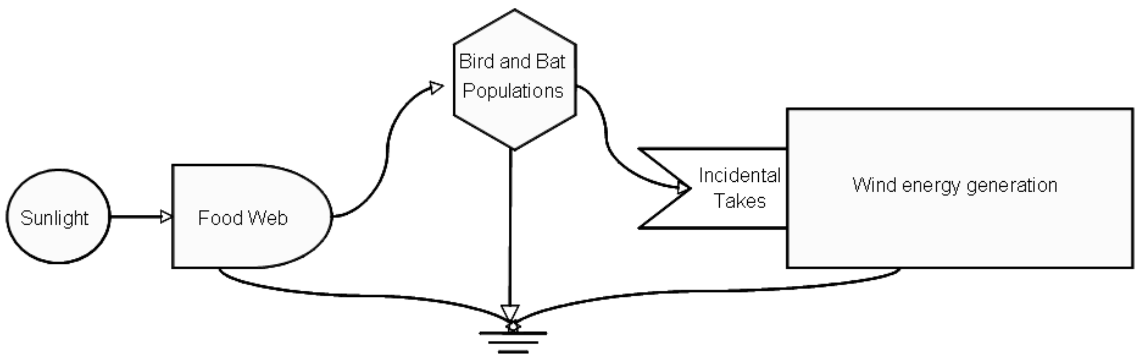


Figure 3. System diagram of adverse wildlife impact associated with wind energy development

Horizon Energy and PPM Energy published a report (PPM Energy and Horizon Energy, 2007) regarding bird and bat impacts at Maple Ridge in the preceding year. The U. S. Fish and Wildlife Service (USFWS), U.S. Army Corps of Engineers (ACE), Environmental Design and Research (EDR), New York State Department of Environmental Conservation, developers (PPM and Horizon), and others reviewed methodology for the analysis. An independent firm conducted the analysis.

Adverse wildlife impacts associated with 120 of the facility's 190 turbines were included in the study. Iterative carcass surveys were performed in the vicinities of each of the turbines throughout the 2006 season. A total of 123 avian carcasses were observed. There was one raptor fatality attributed to rotor collision (*Falco sparverius*, an American Kestral). Twenty-six species of songbirds, one ruffed grouse, and two Canada

Geese were also killed by rotor collisions. There were no carcasses of threatened or endangered species observed. A total of 326 bat carcasses were observed. Five species of bats were observed. No carcasses of threatened or endangered bats were observed. All species observed have been designated by the International Union for Conservation of Nature and Natural Resources as “species of least concern” (PPM Energy and Horizon Energy, 2007).

Researchers performed mortality transects at certain turbines every 7 days, others every 3 days, and others daily throughout the season. The greatest numbers of mortality incidents were recorded at turbines searched daily. At turbines searched daily, there were 9.59 bird incidents/turbine/season and 24.53 bat incidents/turbine/year (PPM Energy and Horizon Energy, 2007).

Appendix B provides a summary of the bird impact data from the 2007 report. The mean biomass of birds impacted at Maple Ridge in 2006 was 14.4 g dry weight. This figure excludes one 6 kg wild turkey discovered by researches that may have been killed by a turbine. Walter (1979) indicates that the energy content of bird biomass is about 20,000 J/g. Therefore, energy lost to the system due to bird mortality may be calculated as follows:

(9.59 birds killed/turbine/season)(195 turbines)(14.4 g dry weight/bird)(20,000 J/g)(20 years)

To calculate emergy lost to the system due to bird mortality, one must first calculate a transformity for birds. Bird transformity may be calculated by dividing the emergy of food consumed by the bird population by the bird energy flow. Energy flow in this context is defined as the total metabolic energy use plus biomass accretion per unit area. Holmes and Sturgis report the average annual energy intake of birds to be 73,858 kcal/ha/yr. Insects were assumed to be the primary forage for the birds in the vicinity of Maple Ridge. The Golden Crowned Kinglet is an insectivore (Holmes and Sturgis, 1979). Since this is the most impacted species (see Appendix B), the aforementioned assumption is fair. The transformity for insects was obtained from the literature (Cohen, 2004) to determine emergy of food consumed. Holmes and Sturgis (1979) also present the average of total avian respiration plus net production for an experimental forest with species diversity comparable to Maple Ridge. The authors found annual avian energy flow to be 51,701 kcal/ha/yr. Figure 4 illustrates how the emergy associated with bird impact is derived from this data. Appendix A provides additional detail.

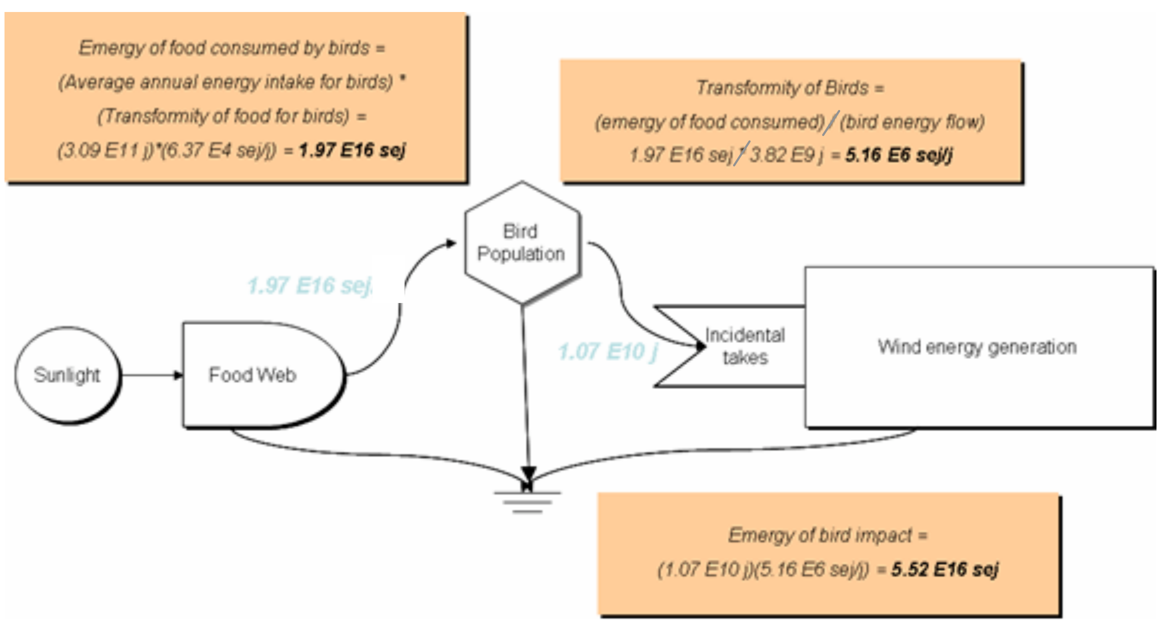


Figure 4. Emergy of bird Impact at Maple Ridge

Appendix C provides a summary of the bat impact data from the 2007 report. The median biomass of bats impacted at Maple Ridge in 2006 was 27 g dry weight. Bat biomass is assumed to have energy content comparable to that of birds. Walter (1979) indicates that the energy content of bird biomass is about 20,000 J/g. Therefore, energy lost to the system due to bat mortality may be calculated as follows:

(24.53 bats killed/turbine/season)(195 turbines)(27 g dry wt/bat)(20,000 J/g)(20 yrs)

To calculate emergy lost to the system due to bat mortality, one must first calculate transformity for bats. Bat transformity may be calculated by dividing the emergy of food consumed by the bat population by the bird energy flow. Energy flow in this context is defined as the total metabolic energy use plus biomass accretion per unit area. de la Cueva Salcedo (2250) determined that the diet of the Hoary Bat consists primarily of moths and other insects. Reddy estimated that the Hoary Bat consumed about 262,800 insects per year. Vshivkova (2003) determined an average energy density of 1895 j/g dry weight for certain moths. The transformity for insects was obtained from the literature (Cohen, 2004) to determine emergy of food consumed. There are few authoritative studies regarding the population ecology of the Hoary Bat, though studies of behavioral ecology suggest they are solitary and have large home ranges (e.g., Shump and Shump, 1982). A modeling tool available through the Foothills Model Forest Network (Foothills Model Forest, 1999; pg HOBA-2) proposes that Hoary Bats thrive at a population density of two individuals per hectare on agricultural land. Therefore, transformity of bats may be calculated as follows:

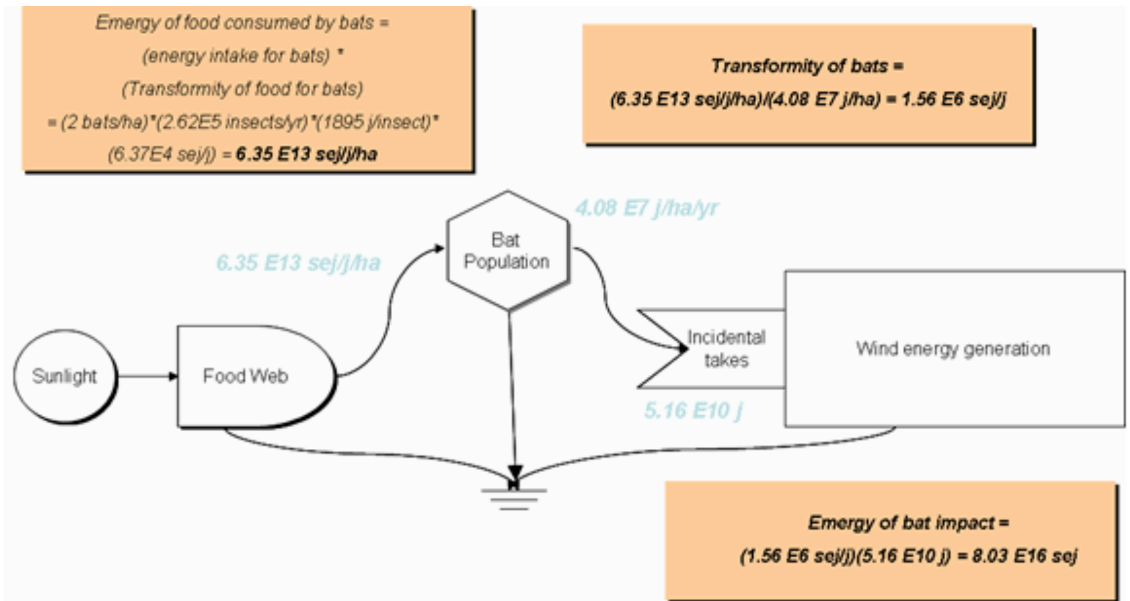


Figure 5. Emergy of bat impact at Maple Ridge

The emergy lost to the system due to bat impact may be calculated by multiplying the transformity by the energy lost to the system. Bat transformity and emergy calculations are provided in Appendix A.

Land Appropriation

Horizon Wind Energy (2007) indicated that 84 hectares of land were taken out of production to support the operation and maintenance of Maple Ridge's 195 turbines. The footprint of a modern wind turbine is very small; most of this appropriation supported the creation of access roads.

During several trips to Maple Ridge in 2006 and 2007, the author of this thesis observed livestock grazing at low density in the vicinity of the turbines. Some land appeared to be under cultivation. Other land was fragmented forest. Brown and Vivas (2005) offer an empower density of 8.14 E14 sej/ha/yr for "woodland pasture with livestock." This empower density is employed to determine the emergy of appropriated land. Land appropriation transformity and emergy calculations are provided in Appendix A.

Material, Labor, and Fuel Inputs

The aforementioned life cycle assessment (Vestas, 2006) offers a detailed breakdown of the material inputs to a V82 wind turbine and support infrastructure like cabling. ABB Power Transmission (2003) offers a breakdown of material inputs to a 500 MVA transformer. A similar transformer was observed at Maple Ridge's Rector Road substation by the author of this thesis. Table 2 summarizes data from these two sources and illustrates the materials inputs necessary to construct a facility such as Maple Ridge.

Table 2. Material Inputs to the Maple Ridge Wind Energy Facility

Material	Weight, g
Tower	
Steel	2.46E+10
Aluminum	5.07E+08
Electronics	4.29E+08
Plastic	3.90E+08
Copper	2.54E+08
Oil (Lubrication)	1.95E+08
Nacelle	
Cast Iron	3.51E+09
Steel	5.28E+09
Fibreglass	3.51E+08
Copper	3.12E+08
Plastic	1.95E+08
Aluminum	9.75E+07
Electronics	5.85E+07
Oil (Lubrication)	5.85E+07
Rotor	
Cast Iron	2.20E+09
Steel	8.19E+08
Epoxy, fibreglass, wood	4.91E+09
Foundation	
Concrete	1.57E+11
Steel	5.27E+09
Internal Cables	
Aluminum	1.24E+10

Material	Weight, g
Plastic	1.08E+10
Copper	6.03E+09
External Cables	
Plastic	2.96E+11
Aluminum	1.86E+11
Copper	4.65E+10
Transformer	
Oil (Lubrication)	6.30E+07
Copper	4.00E+07
Insulation	6.50E+06
Wood	1.50E+07
Poreclain	2.65E+06
Steel	1.53E+08
Paint	2.20E+06

Electricity Output

The rated, or nameplate capacity of the V82 is 1.65 MW. When wind is blowing within an optimal range of velocities, the turbine will produce electricity at a rate of 1.65 MW, e.g., if the wind blows within this range for an hour, the turbine will generate 1.65 MWh of electricity. The capacity factor is the number by which the rated capacity is multiplied to determine the actual electricity generation potential of a turbine or a facility. The capacity factor is a function of site characteristics such as average annual wind speed and topography. Bill Moore, principle developer of the Maple Ridge wind power project suggested that the capacity factor of the facility would eventually be about 0.33 (Personal communication, 2007). This figure comports with capacity factors at other modern wind power installations (Tester, 2005).

Given the 20-year anticipated project lifecycle, one may estimate the electricity generation potential of the facility in MWh using the following calculation:

(1.65 MW)(0.33)(195 turbines)(24 hrs/day)(365 days/yr)

A transformity from the literature for electricity is employed in the emergy analysis. Electricity is employed in the EROI and emergy analyses. Results from the EROI analysis are listed in Table 3. Results from the emergy analysis are listed in Table 4. Endnotes associated with the EROI and emergy analyses are in Appendices D and A, respectively.

Table 3. EROI analysis of the Maple Ridge Wind Energy Facility (see Appendix D for notes)

Note	Item	Data	Unit
1	Energy Intensity of the US Economy, 2006	8.22 E6	j/$ (2006)
2	Cost of the Maple Ridge Wind Energy Facility	3.5 E8	$
3	Energy Invested	2.9 E15	j
4	Lifecycle Electricity Output	6.7 E16	j
5	Energy Return on Investment (EROI)	20.93	

Table 4. Emergy analysis of Maple Ridge Wind Energy Facility (see Appendix A for notes)

Note	Item	Data	Units	Emergy/unit (sej/unit)	Solar Emergy (sej/20yrs)
Renewable					
1	Wind	2.21 E15	j	2,513	5.54 E18
2	Land Appropriation	84	ha	8.00 E14	1.34 E18
3	Bat Impact	5.16 E10	j	1.56 E6	8.03 E16
4	Bird Impact	1.07 E10	j	5.16 E6	5.52 E16
Material					
5	Concrete	1.57 E11	g	1.44 E9	2.26 E20
6	Steel	3.65 E10	g	3.38 E9	1.23 E20
7	Fiberglass and Composites	5.27 E9	g	7.87 E9	4.15 E19
8	Aluminum	2.51 E9	g	1.27 E10	3.19 E19
9	Copper	2.96 E8	g	6.80 E10	2.01 E19
10	Cast Iron	5.71 E9	g	3.38 E9	1.93 E19
11	Computer Equipment	4.88 E8	g	7.76 E9	3.79 E18
12	Lubricants	1.31 E13	j	6.60 E4	8.65 E17
13	Plastics	2.10 E9	g	3.80 E8	7.98 E17
14	Paint	2.20 E6	g	1.50 E10	3.30 E16
15	Wood	1.50 E7	g	8.08 E8	1.21 E16
16	Insulation	6.50 E6	g	1.50 E9	9.75 E15
17	Porcelain	2.65 E6	g	3.06 E9	8.11 E15
Labor and Fuel					
18	Services	3.50 E8	$	8.00 E11	2.80 E20
19	Labor (O&M)	8.00 E2	man yrs	2.80 E17	2.24 E20
20	Labor (Decommissioning)	6.00 E2	man yrs	9.40 E16	5.64 E19
21	Fuel (Decommissioning)	1.87 E8	g	9.4	5.52 E17
Electricity Output					
22	Electricity	6.70 E16	j	1.59 E5	1.07 E22

Calculation of Indices

Emergy indices have been calculated in accordance with the techniques described in the methodology chapter. Emergy indices are presented in Table 5. EROI is calculated in accordance with the technique described in the methodology chapter. EROI is also presented in Table 5.

Table 5. Summary of calculated sustainability indices. *R* is the sum of values 1-4 in Table 4. *N* is the sum of values 5-21 in Table 4. *Y* is value 22 from Table 4.

Sustainability Index	Calculation	Sustainability Indices for Maple Ridge
Emergy Yield Ratio	Y=1.07 E22 sej F=N+R=1.03 E21 sej EYR=Y/F= 10.34	10.34
Environmental Loading Ratio	N = 1.03 E21 sej R = 7.02 E18 sej ELR = N/R = 146.52	146.52
Emergy Index of Sustainability	EYR = 10.34 ELR = 146.52 EIS = EYR/ELR = 0.07	0.07
Energy Return on Energy Invested	Energy Invested = 2.9 E15 j Lifecycle Electricity Output = 6.7 E16 EROI = 6.7 E16 j /2.9 E15 j	23.1

CHAPTER 4. DISCUSSION

Figure 6 illustrates where Maple Ridge falls among energy generating technologies in terms of Emergy Yield Ratio. EYR values for other energy generating facilities were gathered from Odum (1996) and Brown and Ulgiati (2003). The dark grey bars represent data gathered from Brown and Ulgiati (2003) and the light grey bars represent data gathered from Odum (1996). These data suggest that Maple Ridge has a high emergy yield per unit emergy input relative to other energy generating technologies.

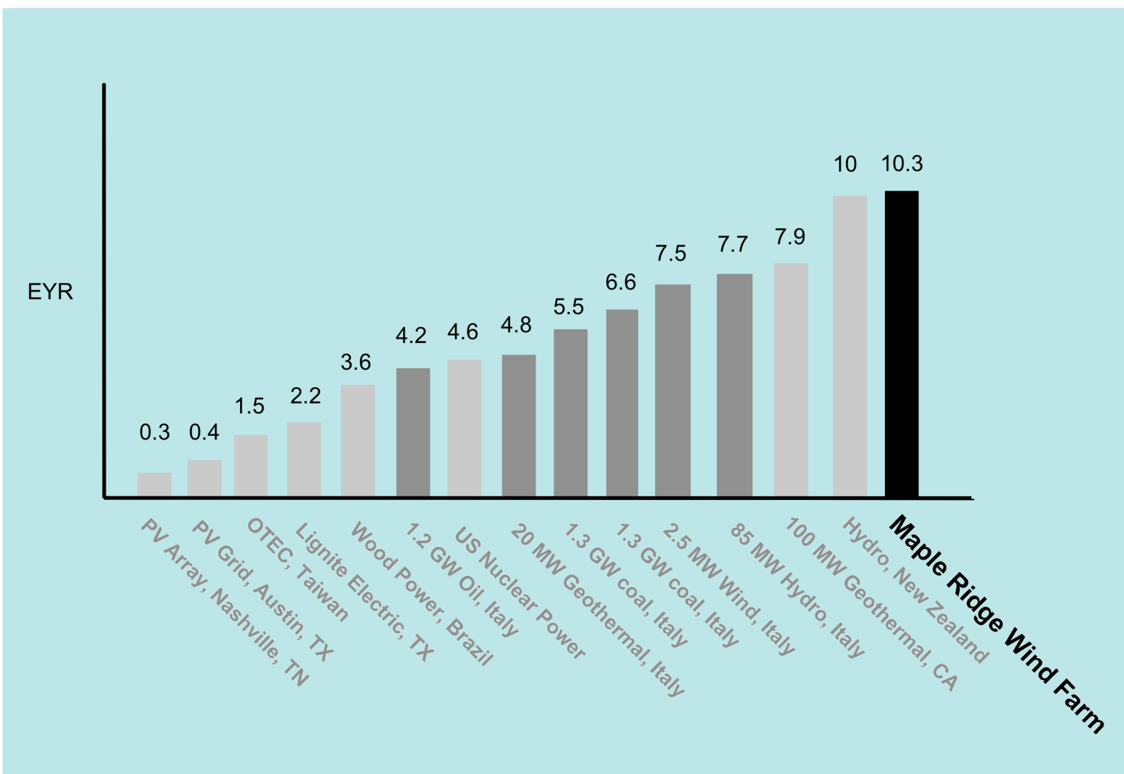


Figure 6. Emergy Yield Ratio for Maple Ridge Wind Energy Facility compared with other energy grenerating technologies (data sources include Brown and Ulgiati, 2003, Odum, 1996, and this study)

Environmental Loading Ratio (ELR) is the ratio of non-renewable to renewable inputs to a given system. ELR for the Maple Ridge Wind Energy Facility is 146.52 which is significantly higher than for other energy generating technologies. For example, Brown and Ulgiati (2002) calculated ELRs of 17.52 for a 1.3 GW oil-fired power plant, 13.5 for a 1.3 GW coal-fired power plant, 0.9 for a 20 MW geothermal plant, and 0.15 for a small wind system. Methodological differences between the Brown and Ulgiati study and this thesis may account for a significant component of the difference in ELR. Brown and Ulgiati employed all wind incident on the wind turbine from the base of the foundation to the tip of the blade as a renewable energy input even though a small fraction of this wind would impact the rotors (Personal Communication, David Tilley, July 2008). Brown and Ulgiati employed a significantly larger denominator to calculate the ELR ratio of their wind system, so one would expect a smaller ELR.

ELR may have limited utility as a metric of sustainability for a wind power facility. A conventional energy facility such as the previously cited 1.3 GW oil-fired power plant draws renewable resources such as water for cooling and employs the environment as a waste sink for exhaust gasses. Abundant non-renewable resources are consumed in the construction, operation, and maintenance of a GW-scale conventional energy power facility. This is a very different kind of environmental load than that exhibited by a wind power facility. Table 4 illustrates that the principle renewable input to the system is the wind the turbines impede to create electricity. Although prodigious quantities of steel and concrete are employed in the construction of a wind facility, such a facility exhibits a very different life cycle energy and material consumption profile than a conventional energy facility.

Environmental Index of Sustainability (EIS) is the ratio of the emergy yield ratio to the environmental loading ratio. EIS for the Maple Ridge Wind Energy facility is 0.07. This is low relative to other electricity generating technologies. For example, Brown and Ulgiati (2002) calculated EISs of 48.3 for a small wind system, 2.7 for a 20 MW geothermal plant, and 0.14 for a 1.3 GW oil-fired power plant. The aforementioned spuriously high ELR is the driver behind the low EIS. The data suggest the aberrant values obtained for ELR and EIS relative to other energy generating technologies are due to methodological inconsistencies rather than deep sustainability implications.

Figure 7 illustrates where Maple Ridge falls among energy generating technologies in terms of energy return on energy invested. EROI values were derived from Cleveland (2005). These data suggest that the Maple Ridge Wind Energy Facility offers a favorable energy return on energy invested relative to other energy generating technologies.

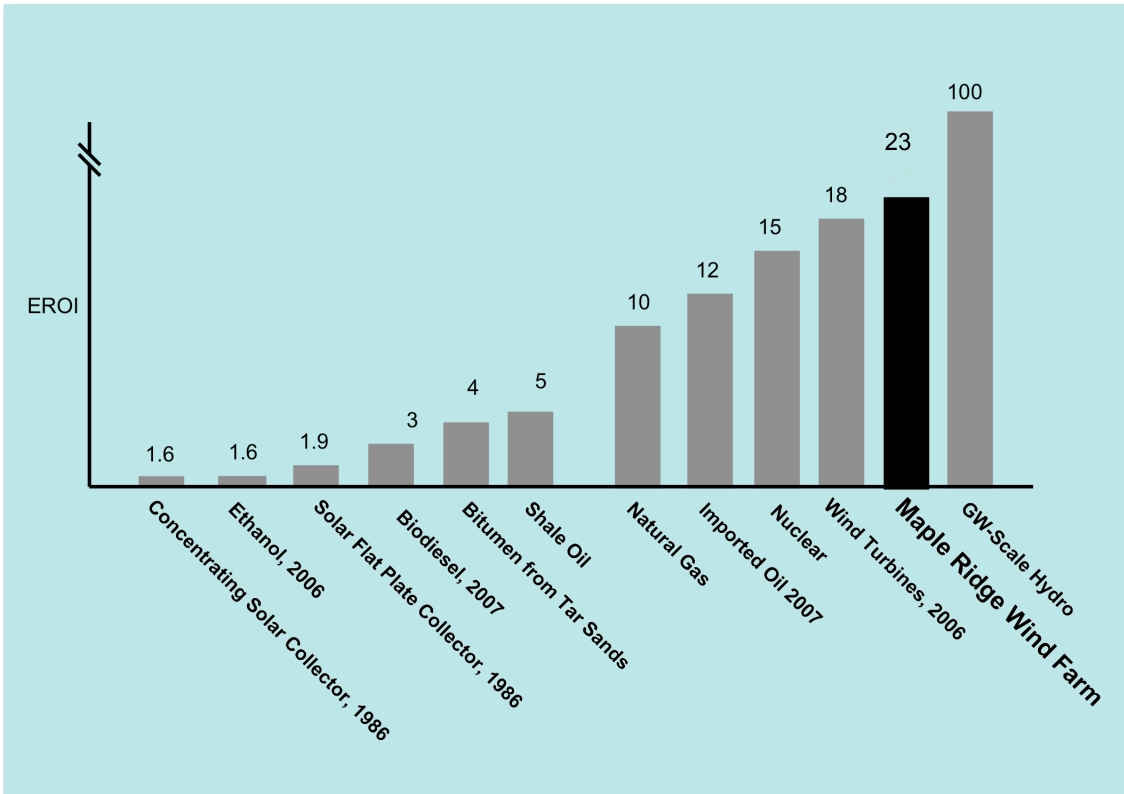


Figure 7. Energy Return on Invested for Maple Ridge Wind Energy Facility compared with other energy generating technologies (data sources are Cleveland, 2005 and this study)

The aforementioned sustainability metrics strongly suggest that Maple Ridge is sustainable relative to other utility-scale energy generating technologies. If Maple Ridge may be regarded as a proxy for utility-scale wind energy development, then these data support the hypothesis that utility-scale wind is a sustainable energy generation alternative.

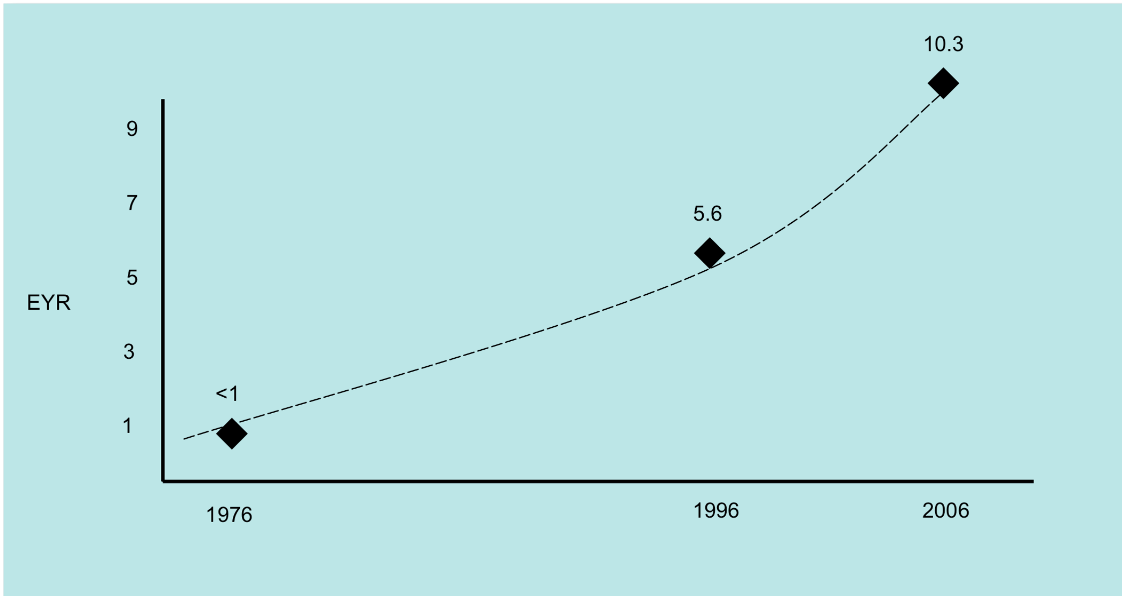


Figure 8. Emergy Yield Ratio over time (data sources include Odum, 1976, Brown and Ulgiati, 2003, and this study)

Trend analysis of EYR over time may bring wind energy's sustainability into sharper focus. At least two other EYR calculations have been performed on early-generation wind energy technologies. The first by Odum (1976) found that conversion of wind into electricity had an emergy yield less than one. Details of the wind system Dr. Odum analyzed were unavailable, but the NASA MOD series were the state of the art at that time. These two-bladed prototype turbines were never deployed at utility scale due to diverse operational issues. For example, the downwind orientation of the rotor relative to the large steel lattice support towers created a dead zone behind the tower. This caused the rotor to violently teeter on its hub with every revolution. In the mid-1970s, the MOD series turbines had nameplate capacities of about 200kW. Brown and Ulgiati (2002) calculated the EYR for a 2.5 MW Italian wind energy facility comprised of ten 250 kW wind turbines and built in 1996. The facility was operated by the municipal utility of Bologna. They found the EYR to be 5.6. Maple Ridge's EYR of 10.3 suggests a trend of increasing emergy yield over time. Figure 8 illustrates this trend.

Many variables may have contributed to this trend. The availability of wind turbines, i.e., the proportion of time that they are operational rather than undergoing maintenance, has increased from less than 20% in the early 1980s to more than 95% in the early 1990. Performance has also increased. Over the same interval, the output of a turbine in a 6 m/s wind regime has increased from below 500 kWh/m2/yr to above 1000 kWh/m2/yr (Turkenberg, 2000). Finally, nameplate capacity has increased from hundreds of kWs to the multi-MW range. The V82s of Maple Ridge have a nameplate capacity of 1.65 MW. Vestas markets a 3.0 MW machine for offshore or onshore applications. Other major manufacturers like GE, Suzlon and Siemens also produce multi-MW machines. Each of these factors increases the amount of electricity generated over the turbine lifecycle; this in turn increases EYR.

EROI for wind energy has also increased over time. Lenzen (2002) compiled more than 20 EROI analyses of wind energy systems conducted since the late 1970s. MW-scale wind energy systems examined by Lenzen are plotted in Figure 9 as diamonds; a trend-line is regressed through these data. While early MW-scale wind systems had EROI values between one and six, several studies (including this thesis) suggest modern machines have values near twenty. Many of the same advances in technology driving the increase in EYR may be driving the increase in EROI.

The trend toward wind energy's increasing EROI comes even as EROI for conventional fossil fuels is declining. Figure 9 also illustrates EROI values for domestic oil production from 1930 to the present developed by Cleveland (2005). Cleveland's research illustrates that EROI has fallen by an order of magnitude since the 1930s. This suggests that progressively more high quality energy inputs are required to extract, process, and deliver energy outputs. If these trends continue, wind may emerge as a critical component in the energy landscape of the future.

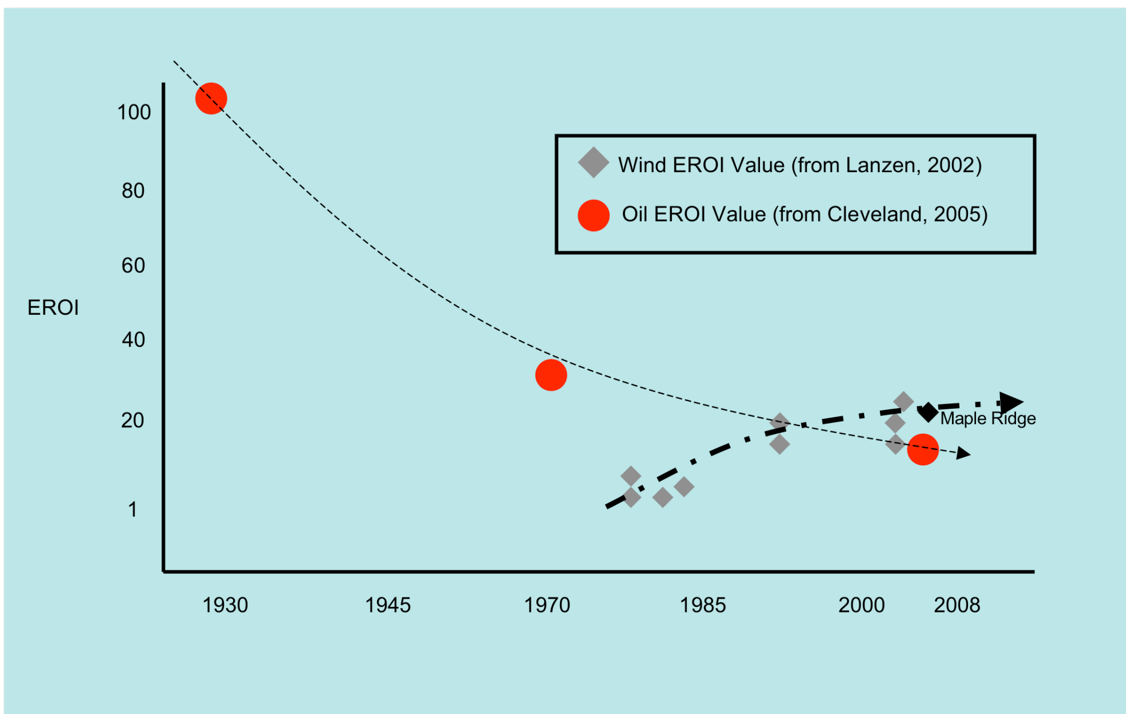


Figure 9. Wind energy's EROI vs. EROIs of the oil and gas industry

Sensitivity Analysis

There is uncertainty associated with many of the data points in the emergy model. Several data points were selected for sensitivity analysis. Points selected included the largest emergy contributors (e.g., services, steel, and concrete), data points which differed from those in published literature (e.g,, Brown and Ulgiati (2002) employed a lower transformity for wind-derived electricity, so a range of transformities were explored), or values which may be controversial by their nature (e.g., transformities for birds and bats). These data were varied by 10% in each direction: 1) the transformity of electricity generated by the Maple Ridge Wind Energy Facility, 2) the transformity of birds, 3) the transformity of bats, 4) the quantity of steel consumed, 5) the quantity of concrete consumed, 5) the cost of the facility, 6) the emergy to dollar ratio, 7) the quantity of wind, and 8) and the quantity of electricity generated by the facility Emergy Yield Ratio was calculated for the aforementioned range of values.

In order to establish upper and lower bounds for EYR, two simulations were performed: one to drive EYR up and another to drive it down. In the simulation to drive EYR up, electricity yield and transformity were increased; emergy input transformities were decreased; and energy, material, and capital inputs were decreased. In the simulation to drive EYR down, electricity yield and transformity were decreased; emergy input transformities were increased; and energy, material, and capital inputs were increased.

The upper bound of EYR is 13.26. The lower bound for EYR is 7.89. The model is most sensitive to changes in the material inputs to the facility and changes to the electricity output of the facility. The model is less sensitive to changes in bird and bat transformity suggesting that the emergy impact of bird and bat fatalities is small relative to the impact of other variables. It is noted that even at the aforementioned lower bound, the EYR is still greater than most other energy generating technologies (see Figure 6). See Appendix E for calculations associated with the sensitivity analysis.

Questions

What are the sustainability implications associated with dramatically ramping up wind power production? What factors will influence the sustainability of wind power moving forward?

Pacala and Socolow (2004) prescribed a massive global increase in wind power capacity to achieve a wedge against climate change. The United States Department of Energy, Office of Energy Efficiency and Renewable Energy (2008) outlined a plan whereby the United States could achieve 20% penetration of wind power on electric grids by 2030 much as the German and Dutch have already done. Wind is currently at less than 1% penetration in the United States.

The sustainability implications for this level of penetration are unknown. Emergy analysis offers unique insight in this regard. Using emergy techniques, the transformity for electricity produced at the Maple Ridge wind energy facility was derived. This transformity was employed in conjunction with Odum's average transformity for electricity generation in a 1:4 ratio to develop a transformity for electricity generation under a 20% wind penetration scenario. This transformity was multiplied by the energy generated by the Maple Ridge Wind Energy Facility to determine the emergy associated with electricity generated in a 20% wind penetration scenario. An Emergy Yield Ratio (EYR) was developed to explore the sustainability implications of 20% wind penetration. See Appendix F for transformity, emergy, and EYR calculation.

EYR for electricity produced in a 20% penetration scenario is 8.5 (see Appendix F). This bodes well for wind energy's prospects as a contributor to the renewable energy landscape of the future. However, there is significant uncertainty associated with this figure.

Table 4 indicates that the capital cost of the Maple Ridge facility represented the single largest emergetic input to the system. Costs associated with wind energy development have been volatile in recent years and are likely to rise in the near and medium term. Turbine infrastructure costs have risen dramatically since the Maple Ridge facility was built for diverse reasons including a global shortage of turbines and components and high commodity prices. If global supply chain issues are not resolved and if commodity prices continue to rise, there will be continued upward pressure on turbine prices (European Wind Energy Association, 2007). This will not only adversely impact the bottom lines of developers; EYR will be adversely impacted as well. Installing transmission infrastructure sufficient to accommodate 20% intermittence will add to the expense of pursuing an aggressive wind strategy. The Department of Energy, Office of Energy Efficiency and Renewable Energy (2008) proposes that profound infrastructure upgrades will be required to accommodate 20% wind and to relieve existing congestion.

Wildlife impact will also affect EYR if wind grows to a greater scale. The magnitude of wildlife impact will increase as wind energy facilities proliferate into migratory flyways and critical habitat. Endangered species will be impacted with increased frequency and regional biodiversity may be threatened. The transformity of endangered species is higher than that of common species (Personal communication, Mark Brown, January, 2008), so the cumulative impact of this phenomenon could be significant in emergy terms. It will likely fuel the growing fire of community opposition to wind turbines. Wildlife impact will pose a significant moral and ethical challenge to the industry.

The data suggest wind achieves high marks for sustainability in a low penetration scenario and slightly lower marks in a high penetration scenario. However, significant uncertainty surrounds the latter figure.

What constrains wind energy growth? What policies would facilitate growth?

Installed capacity of wind power in the United States grew 45% in 2007 (Global Wind Energy Collaborative, 2008). Drivers for this growth included policy and market incentives including Renewable Portfolio Standards and the Production Tax Credit. The industry is poised for additional growth. The American Wind Energy Association and the Department of Energy are charting a course for 20% penetration by 2030 (DOE/EERE, 2008). For reference, wind presently has achieved less than1% penetration nationally (Global Wind Energy Collaborative, 2008). However, further expansion will face diverse challenges. These challenges include the intermittency of the PTC, community opposition, a global supply chain bottleneck, and transmission access.

The intermittency of the PTC

Chapter 1 describes the critical role the Production Tax Credit plays in incentivizing the installation of wind turbines. The credit currently offers $0.019 for each kWh of qualifying renewable energy generated. The PTC was first enacted as part of the Energy Policy Act of 1992 and designed to sunset in 1999. This early iteration of the PTC only subsidized only wind and certain bioenergy resources. After a brief lapse, the PTC was extended for two years in December 1999. After 2001, the tax credit was not reinstated until March 2002. Congress allowed the credit to expire for a third time in 2003; it was not reinstated until October 2004. Another PTC extension passed the senate and was

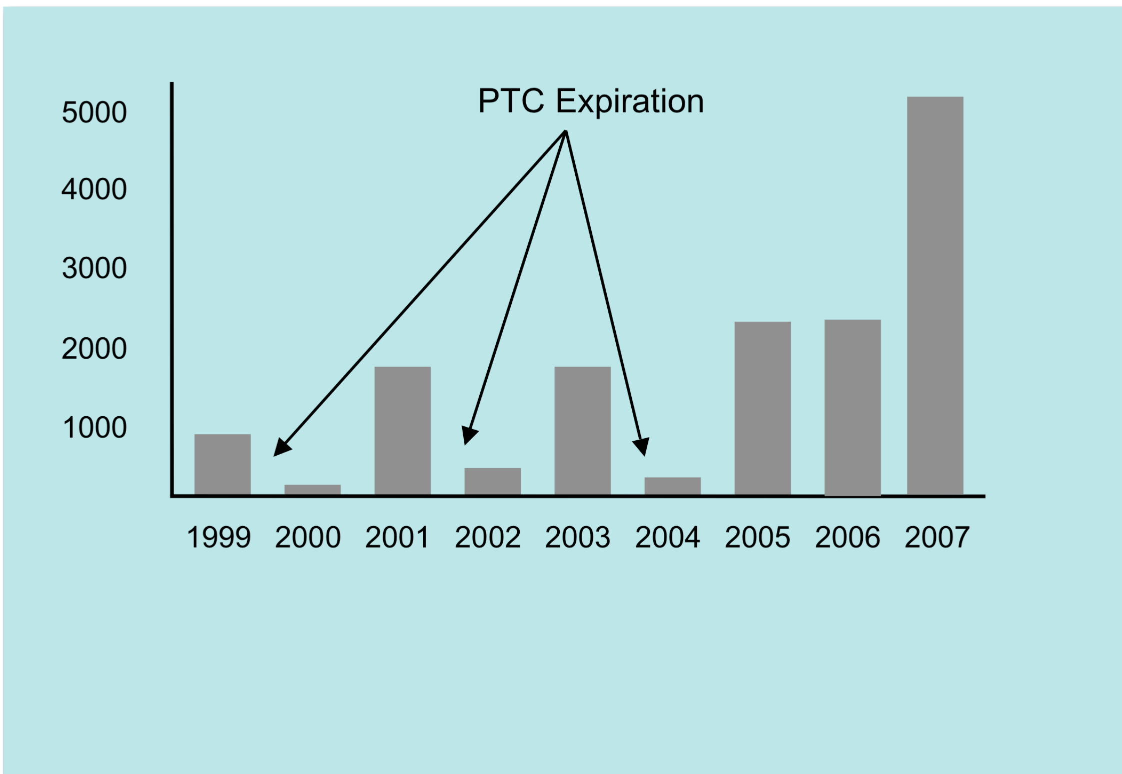


Figure 10. PTC expiration and boom-bust cycles in the wind energy industry

submitted to the house on 11 April 2008 (Tester, 2005). Unless the house takes action before December 31, 2008, the PTC will expire again.

The intermittency of the PTC introduces uncertainty and risk into the renewable energy marketplace. Lending institutions are loath to finance developments in an atmosphere of risk and uncertainty, so development slows dramatically during intervals when the future of the PTC is uncertain. Figure 10 illustrates the historical impact of the PTC's intermittency on wind development. The figure was adopted from a white paper on the legislative priorities of the American Wind Energy Association (Severn, 2008).

In addition to these boom bust cycles, the intermittency of the PTC also discourages the creation of healthy domestic wind infrastructure manufacturing and support services industries. As a result, turbine hardware and support services must be imported. The lack of sustained government support has been cited as one reason why the industry's center of gravity remains in Europe. Eric Thumma, Director of Policy and Regulatory Affairs for Iberdrolla USA, advocates a permanent extension of the PTC. "A permanent PTC is atop everyone's wish list," said Mr. Thumma. "Without a reliable PTC, the domestic industry will never mature," he said (Personal communication, July, 2007).

Community Opposition Based on Aesthetic Concerns

Modern wind turbines may exceed 100 meters. Due to economies of scale, wind energy facilities are typically comprised of dozens or hundreds of turbines. Wind energy facilities are therefore a highly confrontational landscape feature. Some people regard wind turbines as complimentary to the landscape, symbols of sustainability. Others regard wind turbines as more sinister symbols.

Dozens of citizen groups throughout the country have mobilized to oppose wind energy developments in their communities. Some groups propose adverse wildlife impacts should preclude development. Others claim lighting and noise issues associated with proposed development would detract from their quality of life. Most note the visual intrusion the machines will impose on the landscape.

Opposition to wind energy is wide spread across the country, but deeply rooted throughout the wind-rich Appalachian Mountains. Residents concerned about industrialization of the landscape have organized in Virginia, West Virginia, Pennsylvania, and elsewhere. Groups and individuals are using legal tactics to challenge developments in the permitting phase. For example, Chicago-based wind developer Invenergy recently proposed a 124-turbine facility in Greenbrier County, West Virginia. The public comment period mandated by Invenergy's application to the West Virginia Public Service Commission elicited more than 1,500 letters from businesses, groups, and individuals; most of them were oppositional in nature (Bolt, 1996). For example, Slatyfork, West Virginia residents Michele Grinberg and Jim Withrow described their perspectives on the impact turbines impart to the viewshed: "Wind turbines in West Virginia are the wrong idea in the wrong place. West Virginia's beauty and corresponding ability to attract tourist dollars and second-residence dollars derives from its beautiful, tight mountain ridges. Once a turbine is in place, one cannot see the ridge, only man-made large ugly machines. The 'viewshed is destroyed," (Bolt, 1996).

An exploration of Appalachia's history reveals a long legacy of natural resource exploitation by corporations foreign to the region. Since the 19th century, corporations have profited from extraction of forest products and fossil fuels at unsustainable rates. Although natural resource industries have been perennial sources of employment for Appalachians, the region has never converted natural resource wealth to sustainable prosperity. For example, Lewis (1998) described the clear cutting of old-growth forests throughout two-thirds of West Virginia in the late 19th century. Natural and capital wealth road out of the region on rail lines and accrued in the population centers on the coast. With deforestation complete, the industry decamped leaving behind thousands of unemployed loggers, barren hillsides prone to landslides, and sediment filled waterways. The land cover change left Appalachians unable to return to agrarian lifestyles and ill-equipped to face the Great Depression. Coal, oil, and natural gas developments have followed similar trajectories. A recent emergy analysis of West Virginia supports the hypothesis that the state is exporting its emergy endowment and receiving little in return. Campbell et al (2005) showed that twice as much emergy was exported as received in 1997. The environmental loading ratio for economic activity in the state was 14, more than 1.5 times higher than the national average. Quality of life indicators were well below national averages.

Wind is the latest in a long line of natural resources to be coveted by the population centers on the coast. This may be a component of the widespread regional antipathy toward wind developments in Appalachia. Beyond wise facility siting, limited tools are available to wind developers to address this problem. In general, wind speed varies with the height above the surface (Bonan, 2002), so wind turbines will always be tall. Ridgelines typically have the most attractive wind resource, so turbines will always impact the viewshed. Although it may not be possible to mitigate the view of a wind turbine, it may be possible to change what that view represents. By engaging with and investing in the communities that host their facilities, wind energy developers could give those communities a stake in the success of the industry. Developers could make investments in infrastructure (e.g., schools, roads) or public services (e.g., EMS, police, fire). To the extent practicable, developers could make a concerted effort to hire local residents for long-term operation and maintenance positions. The scale of community opposition will grow as the industry grows, so developers would be well advised to tackle this problem now.

Global Supply Chain Bottleneck

Wind Directions (European Wind Energy Association, 2007) described the extent to which surging demand, constrained supply, and high commodity prices have created bottlenecks along the wind energy supply chain. On the demand side, inconsistent policy programs have made long term programming impossible for players in the wind energy industry. The most obvious example of this phenomenon is the PTC. Boom-bust cycles introduced by the intermittence of the PTC discourage domestic investment in infrastructure at each link on the supply chain. The legacy of the PTC's intermittency is a dysfunctional domestic industry beholden in many ways to the more mature industry in Europe. On the supply side, global production capacity of certain components is sharply limited. Gearboxes and bearings are in particularly short supply. Anecdotal evidence suggests that the cranes required to construct these ever-larger machines are also limited (Personal communication, Bill Moore, Maple Ridge Project Manager, PPM Energy, 2007). The prices of requisite raw materials have risen dramatically. Aluminum is trading on the New York Merchantville Exchange at more than four times its 2001 price. Steel, copper, and other commodities have followed similar trajectories, presumably following oil's lead. The dollar's weakness against the euro and other currencies exacerbates the adverse impact of high commodity prices.

Most experts agree that the extant supply side bottlenecks will be resolved in the 2009-2010 timeframe (Wind Directions, 2006). However, the domestic industry will face significant challenges thereafter associated with high commodity prices and a weak dollar. Commodity prices are outside the jurisdiction of policy makers. Policy should be directed toward fostering a domestic industry. Creating a permanent PTC would go a long way toward achieving this goal.

Transmission Access

Wind resource and population centers are infrequently collocated. One consequence of this phenomenon is that some of the most wind-rich regions of the country have limited electricity transmission access. The American Wind Energy Association advocates a massive investment in transmission infrastructure to connect the wind resource in the Great Plains and elsewhere with the population centers on the coasts. They advocate the development of National Renewable Energy Zones within which access to transmission would be plentiful and permitting processes would be expedited (AWEA, 2006).

AWEA cites data suggesting that an investment of $13 billion would be required to connect the Dakotas to the New York City area with a 5,000 mile, 765 kV DC transmission line. The investment would enable the development and delivery of 16 GW installed capacity. This quantity of electricity could substantially meet the needs of the New York City metropolitan area, though conventional capacity would probably be required to follow the load. The investment would pay for itself in about 20 years given the avoided cost of fuel. AWEA (2006) proposed that such an investment would also yield dividends in terms of increased grid reliability and employment opportunities in rural areas.

The total scale of investment required to connect wind-rich regions in the center of the country with the population centers in the coast will be massive. However, if civilization hopes to achieve a stabilization wedge using wind, requisite investments will either have to be made or civilizations will have to relocate to renewable energy rich regions.

Due to wind's intermittency, wind turbines generate electricity erratically. Should a lower transformity be employed reflecting the lower utility of wind-derived electricity?

Isolated wind energy systems operating independently of the grid are poorly suited to applications such as powering a refrigerator or an air conditioner. These appliances require on-demand electricity availability that only the grid or a sophisticated (and expensive) battery bank can provide. Maple Ridge, however, is a 320 MW grid-connected system managed by the New York Integrated Service Operator (ISO). NYISO seamlessly and automatically integrates power from Maple Ridge into the grid as the facility comes on line. Natural gas facilities and other 'peaker plants' are throttled down as Maple Ridge and other wind energy facilities come on line; the peaker plants are engaged again once the wind abates and power production at Maple Ridge ceases. These peaker plants are not devoted to playing the role of wind energy's ballast. They may also engage when fossil fuel or nuclear facilities are off line for scheduled or unscheduled maintenance.

Electricity generated by Maple Ridge is seamlessly integrated into the grid by the ISO. Therefore, it is appropriate to employ an average transformity for electricity produced by the facility.

Conclusion

The New York Times (1919) editorial page published a lament regarding wind electric generation: "It is strange that this free and universal source of power is but little used by us. It will work for you all day and all night and it is very easily utilized." In the breathless prose of an early 20th century editorial page, the Times criticized those who opposed wind turbines for aesthetic reasons and encouraged research into wind electric generation. Nearly a century later, the Times' editorial page still sounds the same refrain. For example, Mckibben (2005) recently advocated the installation of a wind energy facility on the site of a former garnet mine in the Adirondack Mountains of Upstate New York (not far from the Maple Ridge facility). He stated that wind energy was "a key component" of the solution to global climate change. He took to task the heal draggers within the Bush administration who have failed to act on climate change. He also criticized activist community groups and conservation organizations mobilized to oppose wind energy developments noting, "In the best of all possible worlds, we'd do without [wind turbines]. But it's not the best of all possible worlds. Right now, the choice is between burning fossil fuels and making the transition, as quickly as possible, to renewable power."

The data compiled herein suggest that wind is a sustainable electricity generation technology. Provided capital costs can be controlled and wildlife impact can be minimized, the data suggest that wind can continue to be a sustainable source of electricity at 20% market penetration in the United States. This research suggests that Mckibben's quick transition to a renewable future can and should be carried out.

Indeed, the transition is already underway. T. Boone Pickens is an 80-year-old Oklahoma oil magnate with a net worth of $3 billion. A life-long Republican, Mr. Pickens was responsible for the 'Swift Boat' ad campaign many believe responsible for sinking John Kerry's (D-MA) presidential bid in 2004. In recent years, Mr. Pickens has renounced his Republican affiliation and begun speaking about the specter of peak oil and gas. Mr. Pickens is investing $6 billion in a 4 GW wind farm in West Texas. The facility will feature more than 2,000 turbines and be spread out over more than 200,000 acres. Six hundred sixty seven turbines have already been ordered from General Electric and several lease agreements have been signed with ranch owners in the region. (Associated Press, 2007). Mr. Pickens has put forth an ambitious and controversial plan to obviate the need for 38% of the nation's oil imports. He advocates building enough wind capacity to supplant all the natural gas used in electricity generation, and then employing the natural gas as a transportation fuel. He characterized the nation's dependence on foreign oil as "a stranglehold on our country that we can't live with" and suggested that wind would ameliorate the situation in the short term. However, he conceded that his plan "isn't going to solve this thing forever. I'll be gone. Younger people are going to say 'Look, we're in a bad spot.' What will happen is you'll go to the hydrogen, you'll go to the electric car, you'll go to something, but you'll have thirty or forty years to bridge to that point" (Associated Press, 2007).

Far beyond that bridge, one can only speculate about the energy landscape, the civilization that will create it, or the prosperity future energy technology will afford. Odum (2001) proposed that energy substitution options presently available have neither the quantity nor the quality to substitute for fossil fuels. He noted that 71% of whole earth empower comes from fossil fuels which are subject to depletion. Odum therefore proposed that global consumption of energy will have to eventually be reduced to less than one-third its current level necessitating either a reduced population or a lower standard of living.

Odum (2001) speculated that wind technology would play a role in a low energy future. He noted that in pre-industrial times, wind played critical roles in propelling ships and driving post mills and that both energy and emergy yield was always greater than one for these processes. This suggests that wind technology may be capable of serving not only as a wedge against climate change in the medium term, but a sustaining force in a post fossil fuel world.

Future Research Topics

1) As wind turbines proliferate into migratory flyways and critical habitat, the magnitude of wildlife impact will increase. Endangered species impacts will increase. What will be the sustainability implications of these phenomena?

2) Rising commodity prices and the global supply chain bottleneck are driving up turbine costs. Credit markets are tightening in the wake of the US mortgage crisis. How

will these phenomena impact industry's ability to deploy wind at the scale envisioned by Pacala and Socolow (2004)? How will the bottom lines of developers be impacted? How will ratepayers be impacted? How will rising capital expenses impact sustainability metrics such as EYR?

3) Community opposition to wind turbines is growing throughout wind-rich regions of the United States. This opposition threatens industry's capability to implement Pacala and Socolow's (2004) vision of wind energy as a wedge against climate change. What policies may be enacted to address the concerns of community groups mobilized against wind energy development, namely: aesthetics, wildlife impact, and tax revenue-related issues? What are best practices for developers operating in communities that are mobilized against development?

4) This analysis focused on utility-scale wind energy generation. What are the sustainability characteristics of distributed wind generators, i.e., small-scale turbines? Are cost curves of small-scale machines adversely impacted by the same global supply chain bottlenecks as utility-scale machines? What are the sustainability characteristics of small wind generators in grid-tied vs. grid-independent applications?

5) Keith (2004) conceded that wind would provide enormous global benefits, but proposed that large-scale use of wind power may alter global climate by extracting kinetic energy from wind and altering circulation and transport in the atmospheric boundary layer. Conversely, Pryor (2005) suggested that climate change threatens to adversely impact the spatial distribution of wind resource in northern Europe and throughout the world. What are the feedbacks between wind energy development and climate change? How do these feedbacks threaten impact the sustainability of the kind of

large-scale wind development envisioned by Pacala and Socolow? Wind operates the Earth's atmospheric-oceanic system, plays critical roles in the hydrological cycle, and builds and erodes soils through mechanical weathering. How will these processes be impacted by an increase in wind electric production?

Appendix A. Endnotes to Table 4: Emergy Analysis Maple Ridge Wind Energy Facility

1. National Renewable Energy Lab (1986) National Renewable Energy Laboratory describes the 1/7 power rule whereby wind speed aloft may be calculated based on anemometer measurements:

$$u/u_o = \{z/z_o]\text{^}1/7$$

where,

u = the wind speed at a reference height

u_o *= the wind speed at a height z*

z_o *= height for which wind speed is under investigation*

AWS Truewind (2007) indicates that wind resource is class 3 throughout the installation. AWEA (2007) indicates that class three resource is characterized by, on average, 6.7 m/s winds at 50 m. Hub height of the Maple Ridge turbines is 82m (Vestas, 2007). Given these data points, one can calculate the wind speed at hub height using the 1/7 power law.

$$6.7/u_o = \{50/82\}\text{^}1/7$$

$$u_o = 7.2$$

Using this velocity, I can calculate the power in the area swept by the rotor.

*P = 1/2 * rho * Area * V^3*

P= 235425966 W

P = 41,246,629,251.61 kWh incident over project lifecycle

P = 1.48E+17 j incident over project lifecycle

In Piggott's text (1997), the author indicated that 59.3 percent efficiency is the "best we can hope for" in accordance with Betz theorm. If we assume this efficiency, the energy available to the turbines is as follows:

*1.48 E17 j * 0.593 = 8.81 E16*

2. Hectares directly appropriated = 84 (Horizon Wind, 2007). Land cover class = pasture, livestock (author's observations, Winter, 2006). Empower density of pastureland with livestock = 8 E14 (Brown and Vivas, 2005). This is the value for "Woodland Pasture (with livestock)". Emergy lost to land appropriation = (84 ha)*(8. E14 sej/ha/yr)*(20) = 1.34 E18 sej.

3. Appendix B suggests that the Hoary Bat (*Lasiurus cinereus*) is by far the most adversely impacted bat species. This species will be used as a proxy for the bat impact at Maple Ridge. There are few authoritative studies regarding the population ecology of the Hoary Bat, though studies of behavioral ecology suggest they are solitary and have large home ranges (e.g., Shump and Shump, 1982). Foothills Model Forest, 1999; pg HOBA-2 suggests 2 individuals per hectare on disturbed land. This comports with Shump and Shump's contention that the Hoary Bat has a large home range. Energy use per individual Hoary Bat = 2.04 E7 j/yr (de la Cueva Salcedo et al, 1998). Total bat energy flow = (2.04 E7 j/yr) (2 individual/ha) = 4.08 E7 j/ha/yr. de Cueva Salcedo indicates that moths are the primary food for Hoary Bats. Reddy (2003) indicates that 262,800 moths are consumed per Hoary Bat per year. Vishivkova (2003) estimates moth energy content at 1895.4 j/individual. Cohen (2004) indicates transformity for 'large aquatic insects" is 6.37 E4 sej/j. Therefore, transformity, Hoary Bat = (2 individuals/ha)*(262,800 insects consumed per bat)*(1895 j/individual)*(6.37 sej/j)/4.08 E7 j/ha/yr) = 1.56 E6 sej/j.

   Bats killed by Maple Ridge over facility lifecycle = 95,667 (PPM Energy and Horizon Energy, 2007). Assumed energy content of biomass similar to bird biomass. Energy content of biomass 20,000 j/g (Walter, 1979; pg 178-180). Lifecycle energy lost to the system = (20 yrs)(95,667 bats/yr)(27 g average weight)(20,000 j/g) = 5.16

E10 j. Lifecycle emergy lost to the system = (5.16 E10 j)(1.56 E6 sej/j) = 8.03 E16 sej.

4. Average annual energy intake or birds is 3.09 E11 j/yr (Holmes RT and Sturgies FW, 1974). Assumed most birds adversely impacted by the Maple Ridge facility are insectivores. Cohen (2004) reports transformity of "large aquatic insects" as 6.37 E4 sej/j. The emergy of food for birds is 1.97 E16 sej/ha. Total avian energy flow 51,701 kcal/ha/yr (Holmes RT and Sturgies FW, 1974). This represents average of total avian respiration plus net production for the years 1969-1973. Transformity, Birds = (1.97 E16 sej/ha)/(51701 kcal/ha/yr * 4184 j/kcal) = 5.16 E06. Birds killed by Maple Ridge facility per year = 1,870 (PPM Energy and Horizon Energy, 2007) [9.59 birds per turbine (high estimate) *195 turbines]. Mean biomass per bird = 14.43 (see Appendix A). Lifecycle biomass lost to the system = (1,870 birds per year)(14.43 g/bird)(20 years) = 539,682 g/20 years. Energy content of bird biomass = 20,000 j/g (Walter, 1979). Lifecycle energy lost to the system = (26,984)(20,000) = 1.07 E10 j. Emergy lost to the system = (1.07 E10 j)(5.16 E06 sej/j) = 5.52 E16 sej.

5. Concrete consumed = 1.57 E11 g (Vestas, 2006). Transformity 1.44 E9 sej/g (Buranakarn, 1998), Emergy = (1.57 E11 g)(1.44 E9 sej/g) = 2.26 E20 sej.

6. Steel consumed = 3.65 E10 g (Vestas, 2006). Transformity = 3.38 E9 sej/g (Odum, 1996). Emergy = (3.65 E10 g)*(3.38 E9 sej/g) = 1.23 E20 sej.

7. Fiberglass and composites consumed = 5.27 E9 g (Vestas, 2006). Includes fiberglass, epoxy, and balsawood framing materials for blades. Transformity = 7.87 E9 sej/g (Burarnakarn, 1998). Used transformity for "float glass". Emergy = (5.27 E9 g)(7.87 E9 sej/g) = 4.15 E19 sej.

8. Aluminum consumed = 2.51 E9 g (Vestas, 2006). Transformity = 1.27 E10 sej/g (Buranakarn, 1998). Emergy = (2.51 E9 g)(1.27 E10sej/g) = 3.19 E19 sej.

9. Copper consumed = 2.96 E8 g (Vestas, 2006). Transformity = 6.8 E10 (Buenfil, 2001; pg 197). Emergy = (2.96 E8 g)(6.8 E10 sej/g) = 2.01 E19 sej.

10. Cast iron consumed = 5.71 E9 g (Vestas, 2006). Transformity = 3.38 E9 (Odum, 1996; pg 186). Used transformity for "Iron and Steel Products". Emergy = (5.71 E9 g)(3.38 E9 sej/g) = 1.93 E19 sej.

11. Electronics employed = 4.88 E8 g (Vestas 2006). Transformity = 7.76 E9 (Campbell, 2005). Used value for "Electronic and Other Electrical Equipment". Emergy = (4.88 E8)(7.76 E9) = 3.79 E18 sej.

12. Lubricants consumed = 2.91 E9 (Vestas, 2006). Energy content of lubricants = 1.31 E13 (employed EIA energy content calculator). Transformity = 66,000 (Odum, 1996; pg 186). Used value for petroleum products. Emergy = (1.31E13 j)(66,000 sej/j) = 8.65 E17 sej.

13. Plastics consumed = 2.1 E9 (Vestas, 2006; pg 16-17). Transformity = 3.8 E8 (Lagerberg and Brown, 1999, pg 429). Emergy = (2.1 E9 g)(3.8 E8 sej/g) = 7.98 E17 sej.

14. Paint consumed = 2.2 E6 g (ABB Power Transmission, 2003). Transformity = 1.5 E10 (Buranakarn, 1998, pg 199). Emergy = (2.2 E6 g)(1.5 E10 sej/g) = 3.3 E16 sej.

15. Wood consumed = 1.5 E7 g (ABB Power Transmission, 2003). Transformity = 8.08 E8 (Buranakarn, 1998, pg 69). Emergy = (1.5 E7 g)(8.08 E8 sej/g) = 1.21 E16 sej.

16. Insulation consumed = 6.5 E6 g (ABB Power Transmission, 2003). Transformity = 1.5 E9 (Brown and Ulgiati, 2002; pg 327). Emergy = (6.5 E6 g)(1.5 E9 sej/g) = 9.75 E15 sej.

17. Porcelain consumed = 2.65 E6 g (ABB Power Transmission, 2003). Transformity = 3.06 E9 (Brown and Buranakarn, 2003; pg 13). Used value for 'Ceramic tile with recycled glass". Emergy = (2.65 E6 g)(3.06 E9 sej/g) = 8.11 E15 sej.

18. Capital cost of the Maple Ridge Wind Energy Facility was $350 million and included trucking and shipping costs (fuel, labor) and all construction costs (D'Estries, 2007). The emergy to dollar ratio for the year the facility was constructed was 8 E11 sej/$. Emergy associated with services = ($350 million)*(8 E11 sej/$) = 2.80 E20 sej.

19. O&M FTE = 40 (William Moore, PPM Energy, Personal communication, May 2007. Mr. Moore was the lead project developer for the Maple Ridge facility. Data regarding FTE is proprietary and changes over the project lifecycle due to unpredictable circumstances, but Mr. Moore indicated that '40' is a good estimate.) Lifecycle man years = 40 * 20 years = 800. Emergy per man year = 2.8 E17 (Odum, 1996; pg 232). Used value for "College Grad." Emergy = (800 man yr)(2.8 E17 sej/man yr) = 2.24 E20 sej.

20. Assumed decommissioning labor will be identical to construction labor. Labor (Construction) includes trucking, crane and rigging, longshore, and other construction operations. (William Moore, PPM Energy, Personal communication, May 2007). Data regarding employment is proprietary, but Mr. Moore agreed that '300' is a good estimate. Comports with estimates in other sources, e.g., Alliance for Clean Energy New York, 2007. (William Moore, PPM Energy, Personal communication, May 2007). Construction lasted about a year according to Mr. Moore. Assumed 1.5 years to provide a conservative estimate of emergy associated with labor. 450 man years. Emergy used per man year = 9.4 E16 (Odum, 1996; pg 232). Used value for

"School," i.e., not college graduates. Emergy = (450 man yrs)(9.4 E16 sej/man yr) = 5.64 E19 sej.

21. Assumed decommissioning fuel use will be identical to construction labor. Fuel (Shipping and Trucking) includes diesel and gasoline for trucking ad bunker fuel for shipping. Tower sections comprise the great majority of a turbine's shipped weight. The Vestas Environmental Statement (Vestas, 2004; pg 93) indicates that tower section are manufactured in and exported from the factory in Varde, DK. Assumed all turbine components were manufactured in and exported from Varde facility. Author's observations, September 2005, indicate that turbine components arrived at the Port of Oswego. GIS analysis indicated 3165 nautical miles from Varde, DK to Oswego, NY. 3165 nm = 5862 km. Freihofer, 2006; pg 1 indicates 25 ships arrived from 2005-06. The author of this thesis observed several ships from the Beluga Fleet in the Port of Oswego offloading turbine components during this interval. The *Beluga Revolution* and other ships of similar size were observed in the Port of Oswego in the Fall of 2005 (See Figure XXXX). Beluga Group, 2007 indicates that R-Class heavy lift carriers like the *Revolution* consume 29 mega tons of "Intermediate Fuel Oil" (bunker fuel) per day when cruising at 18 knots (~33 km/hr). [(5862 km)/(33 km/hr*24 hrs/day)]*(29 metric tons/day)*(25 ships)(2 trips per ship) = 1.7 E10. Transformity of shipping fuel = 2.95 E9 (Carrarretto, 2004; pg 2209). Emergy, shipping fuel = (1.7 E10 g)(2.95 E9 sej/g) = 5.02 E19 sej. Trucking distance, Port of Oswego to Lewis County construction site = 75 miles (authors estimate). Freihofer, 2006; pg 1, indicates that the facility is comprised of (i.e., rolled of the docks as) 1755 independent pieces. Author's observations indicate that blades must be shipped dedicated trucks, but that many nacelles and other components may be shipped in the same truck. Estimated 1000 total truck trips to deliver the 1755 independent pieces. 2000 total trips including return trips. (150 miles)(2000 one-way trips) = 300,000 miles. Estimate mpg of 7. 300,000/7 = 42,857 gallons. Fuel weight = 1.42 E8 g (used fuel weight calculator at changinggears.com). Transformity = 2.95 E9 sej/g (Carrarretto, 2004; pg 2209). Emergy, trucking fuel = (1.42 E8 g)(2.95 sej/g) = 4.18 E17. Author observed Ford Ranger pick up trucks escorting 18-wheelers to the

construction site. FuelEconomydb.com, 2007 indicates that the Ford Ranger gets about 24 mpg in mixed highway, city driving conditions. Freihofer, 2006; pg 1 indicates that a blade truck requires three escorts while other trucks require only two. The 195 turbines at Maple Ridge have 585 total blades (585*3). Blades require dedicated trucks. Therefore 415 18-wheelers required only two escorts. [(415 18 wheelers)(2 escorts each)(150 miles)]+[(585 18 wheelers)(3 escorts each)(150 miles)] = 387,750. Total fuel use, escort = (387,750 miles)/(24 mpg) = 16,156 gallons. Fuel weight = 4.5 E7 (used fuel weight calculator at changinggears.com). Transformity = 2.95 E9 sej/g (Carrarretto, 2004; pg 2209). Emergy, escort fuel = (2.4 E7 g)(2.95 E9 sej/g) = 1.3 E17 sej. Total emergy of fuels used = (5.02 E19)+(4.18 E17)+(1.3 E17) = 5.52 E19 sej.

22. Nameplate capacity of wind power plant = 312.75 MW. Maple Ridge is a new facility. Capacity factor has fluctuated widely as technical problems have arisen, and then been resolved (William Moore, personal communication, May 2007). Tester (2006) indicates that 0.33 is a rule-of-thumb capacity factor for terrestrial wind farms. Estimated lifecycle power production = (321750 kW)(0.33)(24 hrs/day)(365 days/yr)(20 yrs) = 1.86 E10 kWh = 6.7 E16 j. Transformity = 1.59 E5 (Odum ,1996; pg 187). Emergy = (6.7 E16 j)(1.59 sej/j) = 1.07 E22 sej.

Appendix B. Bird Mortality at Maple Ridge Wind Energy Facility, 2006

Species	Observed Fatalities, All Sites[1]	Biomass, g[2]
Gold Crowned Kinglet (Regulus satrapa)	22	6
Wild Turkey (Meleagris gallopavo)	3	5,700
American Kestral (Falco sparverius)	1	122
Common Grackle (Quiscalus quiscula)	1	120
American Goldfinch (Carduelis tristis)	1	13
American Redstart (Setophaga ruticilla)	2	8.9
Blackburnian Warbler (Dendroica fusca)	2	10.4
Blackpoll Warbler (Dendroics striata)	1	12
Black-throated Blue Warbler (Dendroica caerulescens)	6	9.9
Black-throated Green Warbler (Dendroica caerulescens)	1	9
Brown Creeper (Certhia familiaris)	3	8.3
Cedar Waxwing (Bombycilla cedrorum)	3	32
Chestnut-sided Warbler (Dendroica pensylvanica)	2	11.1
Cliff Swallow (Petrochelidon pyrrhonota)	1	8
Eastern Phoebe Flycatcher (Sayornis phoebe)*	1	15.3
Hermit Thrush (Catharus gattatus)	1	30
Magnolia Warbler (Dendroica magnolia)*	6	10
Ovenbird (Seiurus aurocapillus)	1	19.5
Palm Warbler (Dendroica palmarum)*	1	10
Philadelphia Vireo (Vireo philadelphicus)	1	12.1
Pine Warbler (Dendroica pinus)*	1	10
Red-Eyed Vireo (Vireo olivaceus)	11	17.6
Red-Winged Black Bird (Agelaius phoeniceus)	1	65
Ruby Crowned Kinglet (Regulus calendula)	1	6
Scarlet Tanager (Piranga olivacea)	2	12
Swainson's Thrush (Catharus ustulatus)	2	30.1
Tree Swallow (Tachycineta bicolor)	1	20
Yellow-belied Sapsucker (Sphyapicus varius)	1	48.3

Yellow-throated Vireo (Vireo flavifrons)*	1	17.6
Unidentified/Other	18	10
Total Observed Fatalities, All Sites	99	-
$\bar{x}$ *(weighted biomass)*	-	14.4**

[1]PPM Energy and Horizon Energy, 2007
[2]Holmes RT and Sturges FW, 1974
** $\bar{x}$ excludes the 3 Wild Turkeys fatalities observed at the facility.

Appendix C. Bat Mortality at Maple Ridge Wind Energy Facility, 2006

Species	Observed Fatalities, All Sites[1]	Biomass, g
Hoary Bat (*Lasiurus cinereus*)	85	34
Eastern Red Bat (*L. borealis*)	23	12
Silver Haired Bat (*Lasionycteris noctivagans*)	27	8
Little Brown Bat (*Myotis lucifugus*)	25	8
Big Brown Bat (*Eptesicus fuscus*)	10	12
Unclassified/Unknown	156	34
$\bar{x}$ *(weighted biomass)*	-	27.6

[1]PPM Energy and Horizon Energy, 2007; pg 43

Appendix D. Endnotes to Table 3: EROI Analysis of the Maple Ridge Wind Energy Facility

1. Energy Intensity of the US Economy, Btu/$ (2000) = 9,113 Btu/$ (2000) (DOE/EIA, 2007). $1 (2006)/$1 (2000) = ~1.17. j/Btu = 1.055. Energy Intensity of the US Economy, j/$ (2006) = [(9,133 Btu/$ (2000))(1055 j/btu)]/$1.17 = 8.22 E6.

2. Cost of the Maple Ridge Wind Energy facility = $3.5 E8 (2006) (D'Estries, 2007).

3. Energy Invested = (3.5 E8 $ (2006))(8.22 E6 j/$ (2006)) = 2.9 E15 j.

4. Rated capacity of wind power plant = 321.75. Maple Ridge is a new facility. Capacity factor has fluctuated widely as technical problems have arisen, and then been resolved (William Moore, personal communication, May 2007). Tester (2006) indicates that 0.33 is a rule-of-thumb capacity factor for terrestrial wind farms. Estimated lifecycle power production, kWh = 1.86 E10. Estimated lifecycle power production, j = 6.7 E16.

5. Energy return on energy invested = (6.7 E16 j)/(2.9 E15 j) = 23.1

Appendix E. Sensitivity Analysis: Upper and Lower Bound Calculation

Lower Bound Calculation

(Red cells represent data points manipulated for the sensitivity analysis.)

		Energy	Units	Transformity	Emergy
1	Wind	2.43E+15	j	2513	6.10E+18
2	Bat Impact	5.16E+10	j	1.71E+06	8.83E+16
3	Land Appropriation	84	ha	8.00E+14	1.34E+18
4	Bird Impact	1.07E+10	j	5.67E+06	6.07E+16
5	Concrete	1.73E+11	g	1.44E+09	2.49E+20
6	Steel	4.02E+10	g	3.38E+09	1.36E+20
7	Fiberglass and Composites	5.27E+09	g	7.87E+09	4.15E+19
8	Aluminum	2.51E+09	g	1.27E+10	3.19E+19
9	Copper	2.96E+08	g	6.80E+10	2.01E+19
10	Cast Iron	5.71E+09	g	3.38E+09	1.93E+19
11	Computer Equipment	4.88E+08	g	7.76E+09	3.79E+18
12	Lubricans	1.31E+13	j	6.60E+04	8.65E+17
13	Plastics	2.10E+09	g	3.80E+08	7.98E+17
14	Paint	2.20E+06	g	1.50E+10	3.30E+16
15	Wood	1.50E+07	g	8.08E+08	1.21E+16
16	Insulation	6.50E+06	g	1.50E+09	9.75E+15
17	Porcelain	2.65E+06	g	3.06E+09	8.11E+15
18	Services	3.85E+08	$	8.00E+11	3.08E+20
19	Labor (O&M)	8.00E+02	man yrs	2.80E+17	2.24E+20
20	Labor (Decommissioning)	6.00E+02	man yrs	9.40E+16	5.64E+19
21	Fuel (Decommissioning)	1.87E+08	g	2.95E+09	5.52E+17
	Total F				1.10E+21
				1.55E+04	1.04E+21
22	Electricity	6.03E+16	j	1.43E+05	8.63E+21
	EYR	7.89			

Upper Bound Calculation

(Red cells represent data points manipulated for the sensitivity analysis.)

		Energy	Units	Transformity	Emergy
1	Wind	1.98E+15	j	2513	4.99E+18
2	Bat Impact	5.16E+10	j	1.40E+06	7.22E+16
3	Land Appropriation	84	ha	8.00E+14	1.34E+18
4	Bird Impact	1.07E+10	j	4.64E+06	4.96E+16
5	Concrete	1.41E+11	g	1.44E+09	2.03E+20
6	Steel	3.29E+10	g	3.38E+09	1.11E+20
7	Fiberglass and Composites	5.27E+09	g	7.87E+09	4.15E+19
8	Aluminum	2.51E+09	g	1.27E+10	3.19E+19
9	Copper	2.96E+08	g	6.80E+10	2.01E+19
10	Cast Iron	5.71E+09	g	3.38E+09	1.93E+19
11	Computer Equipment	4.88E+08	g	7.76E+09	3.79E+18
12	Lubricans	1.31E+13	j	6.60E+04	8.65E+17
13	Plastics	2.10E+09	g	3.80E+08	7.98E+17
14	Paint	2.20E+06	g	1.50E+10	3.30E+16
15	Wood	1.50E+07	g	8.08E+08	1.21E+16
16	Insulation	6.50E+06	g	1.50E+09	9.75E+15
17	Porcelain	2.65E+06	g	3.06E+09	8.11E+15
18	Services	3.15E+08	$	8.00E+11	2.52E+20
19	Labor (O&M)	8.00E+02	man yrs	2.80E+17	2.24E+20
20	Labor (Decommissioning)	6.00E+02	man yrs	9.40E+16	5.64E+19
21	Fuel (Decommissioning)	1.87E+08	g	2.95E+09	5.52E+17
	Total F				9.72E+20
				1.55E+04	1.04E+21
22	Electricity	7.37E+16	j	1.75E+05	1.29E+22
	EYR	13.26			

Appendix F. Emergy Yield Ratio Calculation Given a 20% Wind Penetration Scenario

1. Transformity for wind energy generated at Maple Ridge was calculated by dividing all the emergy inputs to the facility by the energy output of the facility. Data was derived from Table 4. Transformity = 1.04 E21 sej/6.7 E16 j = 1.55 E4 sej/j

2. The Maple Ridge transformity was multiplied by a factor of 0.2 to simulate 20% penetration of wind electricity. The average transformity for electricity (Odum, 1996) was multiplied by 0.8 to simulate 80% conventional energy generation. These partial transformities were added to determine a transformity for electricity under a 20% wind penetration scenario. Transformity = (1.55 E4 sej/j)(0.2) + (1.59 E5 sej/j)(0.8) = 1.3 E5 sej/j

3. This transformity was multiplied by the energy generated by Maple Ridge over the project lifecycle to determine lifecycle emergy.

4. Emergy Yield Ratio (EYR) was calculated by dividing the emergy yield associated with electricity production by the emergy inputs to the system. EYR = (8.73 E21 sej)/(1.03 E21 sej) = 8.47

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