Momentum

Volume 1 | Issue 1 Article 19

4-18-2012

Wind Energy Development and Theories of Technological Change

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Abstract
The development of low emission, high output electricity generation systems is a focal point of global efforts to reduce anthropogenic effects of climate change without compromising opportunities for economic and social growth. Applications of wind energy technologies for large-scale production have been effective in meeting electricity demand to varying degrees on the international scale. While the wind energy industry has grown significantly in the United States over the past decade, its contribution to overall production has been limited at both the national and local levels of implementation. Wind technologies' incompatibility with the national energy infrastructure is a major barrier to their incorporation into the overall US energy landscape. The current infrastructure was built around coal-fired systems, which have persisted as the primary means of meeting the electricity demand from the nineteenth century onward. Use of wind energy resources is constricted by inconsistencies with traditional development. I use traditional theories of technological change applied to the current electricity system in order to show how wind energy technologies challenge social conceptions of energy production and distribution. Opposition at the community level is often the lethal blow to major wind development projects, as I highlight through a case study of the first proposed offshore wind project in the US. Local interests groups reacting to threats wind farms pose to the town's economy, ecosystems, and social welfare are strong forces in the permitting and financing process. Just as national history of energy production influences the ability of wind power to compete with coal-fired electricity, regional histories shape cultural views of relationships between humans, nature, and resource use. Economic concerns arise based on the succession of dominant industries, each change altering the region's political and local interest group power hierarchies.

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Honors Thesis for Science, Technology and Society
University of Pennsylvania
December 2011

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Abstract

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Section I—US Energy Outlook

The need for changes in the system of energy production, distribution, and consumption must be evaluated before addressing the issues that limit the use of wind energy in shifting the fossil fuel generation paradigm. While technical improvements to mining processes and exploration techniques raise the possibility of discovering fossil fuel reserves, the US Energy Information Administration estimates that, at current consumption rates, proven US coal reserves will be depleted beyond practical use in 250 years.[1] Estimates of the number of years remaining for oil usage are more difficult to project accurately, as the market is dominated by fewer major players—namely, the Organization of Petroleum Exporting Countries (OPEC)—that have the institutional capacities to protect their financial interests and promote steady income for their countries. In addition to the possibility that reserves are being reported with potential price fluctuations in mind, developing and industrialized nations, including the US, are opening new reserves using technologies capable of mining below the ocean floor, converting oil sands and shale gas to usable products, and transporting energy sources from less-exploited areas to regions with limited access to fossil fuels. The complex task of accounting for these market characteristics and the industry's biases in reporting has resulted in an International Energy Agency prediction of 40 years; the same estimate has been reported several years in a row. The 2003 US EIA estimates of natural gas reserves were perhaps the most daunting, setting the

[1] Roger Hinrichs and Merlin Kleinbach. *Energy: Its Use and the Environment*, fourth edition. Toronto: Thomson Books, 2006, 15.

depletion time at just nine years.[2] In terms of electricity production, this is a concerning figure: 23-25% of electricity produced in the US each year is from the combustion of natural gas.[3] Even with anticipated gains in efficiency and new methods of extracting and refining natural gas—which also presents economic barriers to wind power implementation—long-term, effective solutions to the US energy problem require increased reliance on renewable energy sources.

Energy Use and Global Environmental Concerns

The slow growth of renewable resource usage, considered in the context of unstable global fossil fuel reserves, necessitates further study of factors restricting the growth of the wind energy industry. In addition to depleted reserves, the urgency to mass-produce "cleaner" electricity is a motive for addressing these barriers. Coal-fired electricity generation systems contribute to growing atmospheric concentrations of greenhouse gases and other pollutants. The Intergovernmental Panel on Climate Change (IPCC), an organization founded by the United Nations to provide comprehensive data and interpretation of findings in climate science, defines greenhouse gases as "those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds." By absorbing the sun's radiation rather than allowing it to reflect back into the atmosphere, these gases trap heat within the surface-troposphere system. The "greenhouse effect" occurs as the concentrations of water vapor, carbon dioxide, nitrous oxide, methane, ozone, sulfur hexafluoride, hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) increase.

[2] Hinrichs & Kleinbach, *Energy: Its Use and the Environment*, 16.
[3] Hinrichs & Kleinnbach, *Energy: Its Use and the Environment*, 16.

Rises in greenhouse gas emissions in the industrial era are associated with unprecedented increases in average global temperatures over the past 50 years , with significant evidence pointing to anthropogenic causes of melting polar ice caps, glaciers, and snow caps.[4]

Fossil fuel use has contributed to rising temperatures by increasing atmospheric concentration of greenhouse gases. From the beginning of the industrial era to 2000, atmospheric carbon dioxide concentration rose 30%. The danger of utilizing fossil fuel combustion for electricity generation is well-established—the IPCC definitively identifies anthropogenic emissions as the cause of the carbon dioxide increase and used its properties as the standard for establishing other molecules' Global Warming Potential (GWP), a measure of a gas's ability to absorb thermal radiation.[5] In targeting areas to improve environmental sustainability, major sources of anthropogenic emissions must be evaluated. One such source is electricity generation from coal and natural gas, which has been responsible for a relatively stable percentage of total emissions over the past two decades (Table 1). Over this same time span, significant reductions have not been achieved, owing to an outdated transmission grid and steady reliance on fossil fuels. Average power plant efficiencies are around 35% and losses to transmission are to be discussed in the next section. Increased consumption and low efficiency has made emissions reductions difficult to attain; in 2009, electricity generation in the US produced 2,154 million metric tons of carbon dioxide equivalent, about 38% of the nation's total.[6]

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[4] Noam Lior, "The Current Status and Possible Sustainable Paths to Energy 'Generation' and Use," Proc. of the 1st International Nuclear and Renewable Energy Conference (INREC10), Amman, Jordan, March 21-24, 2010.

[5] Hinrichs & Kleinbach, *Energy: Its Use and the Environment*, 297-300.

[6] US Environmental Protection Agency, Inventory of Greenhouse Gas Emissions and Carbon Sinks, 1990-2009, April 15, 2011.

Table 1: CO_2 Emissions from Fossil Fuel Combustion by Fuel Consuming End-Use Sector (Tg or million metric tons CO^2 Equivalent)

End-Use Sector	1990	2000	2005	2006	2007	2008	2009
Transportation	**1,489.0**	**1,813.0**	**1,901.3**	**1,882.6**	**1,899.0**	**1,794.6**	**1,724.1**
Combustion	1,485.9	1,809.5	1,896.6	1,878.1	1,894.0	1,789.9	1,719.7
Electricity	3.0	3.4	4.7	4.5	5.0	4.7	4.4
Industrial	**1,533.2**	**1,640.8**	**1,560.0**	**1,560.2**	**1,572.0**	**1,517.7**	**1,333.7**
Combustion	846.5	851.1	823.1	848.2	842.0	802.9	730.4
Electricity	686.7	789.8	737.0	712.0	730.0	714.8	603.3
Residential	**931.4**	**1,133.1**	**1,214.7**	**1,152.4**	**1,198.5**	**1,182.2**	**1,123.8**
Combustion	338.3	370.7	357.9	321.5	342.4	348.2	339.2
Electricity	593.0	762.4	856.7	830.8	856.1	834.0	784.6
Commercial	**757.0**	**972.1**	**1,027.2**	**1,007.6**	**1,041.1**	**1,031.6**	**985.7**
Combustion	219.0	230.8	223.5	208.6	219.4	224.2	224.0
Electricity	538.0	741.3	803.7	799.0	821.7	807.4	761.7
U.S. Territories[a]	**27.9**	**35.9**	**50.0**	**50.3**	**46.1**	**39.8**	**41.7**
Total	**4,738.4**	**5,594.8**	**5,753.2**	**5,653.1**	**5,756.7**	**5,565.9**	**5,209.0**
Electricity Generation	**1,820.8**	**2,296.9**	**2,402.1**	**2,346.4**	**2,412.8**	**2,360.9**	**2,154.0**

Note: Totals may not sum due to independent rounding. Combustion-related emissions from electricity generation are allocated based on aggregate national electricity consumption by each end-use sector.

[a] Fuel consumption by U.S. territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report.

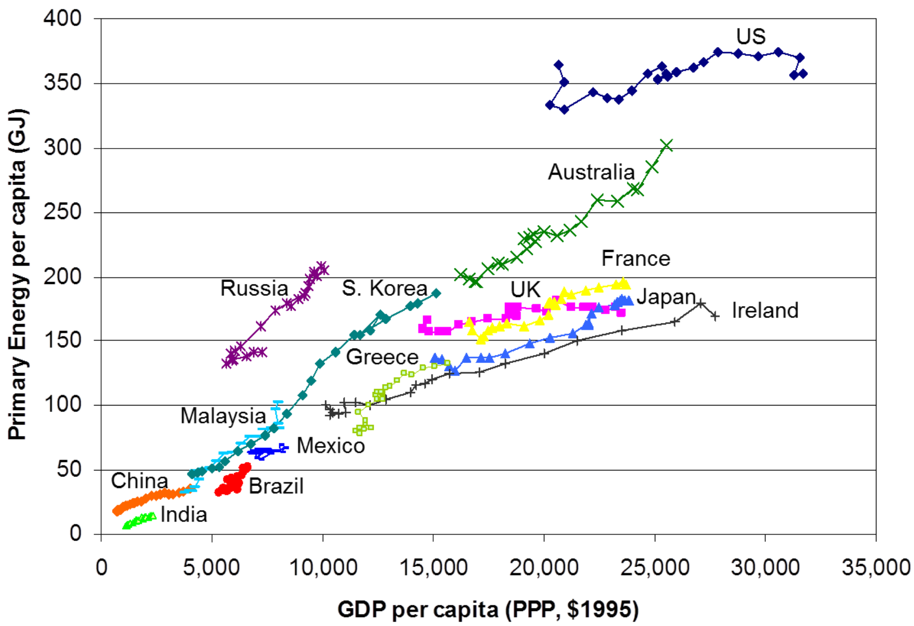
Source: Hinrichs & Kleinbach, Energy: Its Use and the Environment

Energy Use and Global Socioeconomic Concerns

The growth of global emissions output in the future will depend heavily upon the energy sources developed in rapidly industrializing areas. Infrastructural development requires investment of funding and resources; however, increasing energy use per capita may not be the only path to achieving measurable economic gains. Figure 1 illustrates the result of a study of the relationship between per capita Gross Domestic Product (GDP) and primary energy use. The US uses more energy per capita than the nations recorded, yet is comparable in economic prosperity with nations using lower levels of energy, such as Australia, the UK, and France. The results suggest that increased consumption does not produce significant economic gains beyond the 150-250 gigajoule level. A similar study of the relationship between energy use and Human Development Index (HDI) incorporates the response of five equally-weighted factors to energy usage: poverty, inequality, unemployment, health, and education. As with

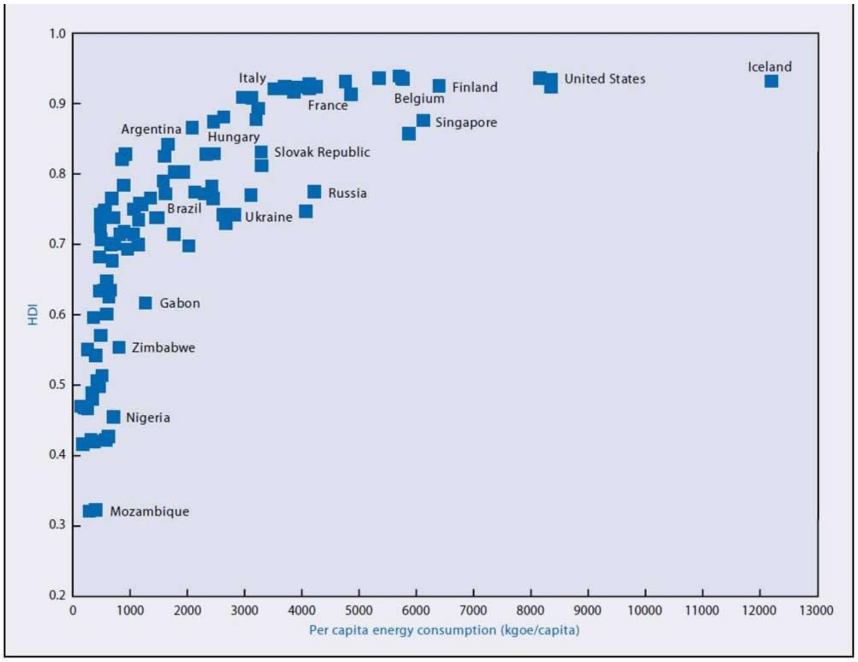
GDP, the social returns for energy consumption appear to be diminishing beyond a certain range.

Figure 1: GDP per capita and Primary Energy Consumption per capita



Source: Lior, "Is reduction of energy use going to harm us economically? A link between national energy consumption and GDP?"

Figure 2: HDI and Energy Consumption per capita



Source: Lior, "HDI (Human Development Index) is not sensitive to energy consumption after a certain minimal consumption is assured"

The US has the highest annual per capita carbon dioxide emissions in the world (Appendix A). Studies of the environmental impact of emissions use various metrics to assess anthropogenic causes of ecological harm. Two of the most common are the Living Planet Index (LPI) and the Ecological Footprint (EF). LPI is a measurement of trends in global biodiversity and accounts for declines in species numbers and degradation of wildlife habitat. The World Wildlife Fund (WWF) and the UN Environment Programme (UNEP) developed the index to better address the impacts of human development. EF measures the relationship between human use and demand on ecological systems, or "human appropriation of ecosystem products and services in terms of the amount of bioproductive land and sea area needed to supply these products and services." EF incorporates six types of land uses—cropland, grazing land, fishing ground, forest land, built-up land, and the uptake land—to calculate the carbon footprint. The numerical value is an estimate of what percentage of the Earth it would take to support humanity; for instance, the footprint in 2006 was 1.4 planet Earths, meaning "humanity uses ecological services 1.4 times as fast as Earth can renew them."[7]

These two metrics grant valuable insight into the impact of human development on environmental sustainability. Since 1970, LPI is estimated to have declined by about 30%, indicating that environmental degradation is occurring rapidly. Over the same period, EF increased 2.4-fold.[8] In a global context, these measures, in tandem with the economic and social indicators reviewed above, are examples of sustainability metrics used in agreements o meet emissions reductions and developmental goals. However, these methods have done little to inform effective policies and abatement actions; according to University of Pennsylvania Professor of Engineering Noam Lior, "we seem to be running out of environment much faster than out of resources."[9] Studies linking GDP, HDI, LPI, and EF to energy consumption provide ample information for policymakers, industry leaders, and global citizens to observe how development has degraded the environment, but methods of aggregating this data and formulating plans for improvement have been ineffective.

Great strides have been made in normalizing economic and environmental data to address the failures of traditional sustainability metrics, but the social pillar of sustainability is perhaps the most difficult to address. This is due in part to the highly localized and individual nature of social "welfare": community, regional, national, and the international values and

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[7] Ecological Footprint Network, *Calculation Methodology for the National Footprint Accounts, 2010 Edition.* 13 October 2010.
[8] Noam Lior, "About sustainability metrics for energy development," Proc. 6th Biennial International Workshop "Advances in Energy Studies", Graz, Austria, 29 June – 2 July 2008.
[9] Lior, "About sustainability metrics for energy development"

human need hierarchies differ, so large-scale changes to energy infrastructure often fail to meet one or several groups' perception of sustainable development. After evaluating the status of wind energy technologies in the next section, wind power's exacerbation of this effect will be addressed in terms of national and local history.

Section II. Wind Energy: Current Use and Potential for Implementation

Global Trends in Usage

Amidst growing awareness of the environmental dangers associated with generating electricity using fossil fuel combustion, integrating renewable energy technologies into the United States electricity supply is a major focus of local and national policies, technical research, and private industry investment. A growing suite of generation systems are capable of meeting a sizeable portion of demand. Wind-powered electricity generation is an option that has enjoyed considerable technical and economic success over the past decade, growing from a global installed capacity of 17.4 gigawatts in 2000 to 194.4 gigawatts in 2010. The increase in installations attests to the feasibility of large wind farm projects and has been efficacious in stabilizing the European Union's electricity supply, currently providing 9.1% of total demand.[10] Although the industry is growing in the US, second only to China in total national capacity, wind-generated electricity supplies less than 3% of the total demand. In an effort to spur greater investment and surpass, the US Department of Energy released a 2011 report entitled *20% Wind Energy by 2030,* outlining its developmental goals for energy infrastructure over the next two decades.[11]

Such goals are important drivers of policies and incentives making wind-generated electricity cost competitive with electricity generated through fossil fuel combustion. Prices paid for electricity are correlated with the costs of production, including fluctuations in fuel prices and operational costs; consumers are sensitive to changes in generation technologies, so

[10] Global Wind Energy Council, *Global Wind Energy Outlook 2010*, October 2010.
[11] U.S. Department of Energy, *20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply,* July 2008.

increasing economic efficiency is vital to widespread implementation. The EU has utilized its strongest wind resources to maximize production from turbines, locating 45 wind farms totaling 2.9 gigawatts of capacity off the coasts of Northern European countries. Offshore production requires a substantial initial investment, comprising a major portion of the €13 billion the EU channeled into wind energy development in 2010.[12] However, wind speeds along coastal areas are more reliable and have higher potential than terrestrial sites. EU channeled into wind energy development in 2010.8 However, wind speeds along coastal areas are more reliable and have higher potential than terrestrial sites and therefore provide an opportunity for long-term economic benefit. The National Renewable Energy Laboratory (NREL) estimates that gross offshore wind generating capacity potential is four times greater than the nation's current supply.[13] A map of the geographical distribution of this potential is in Appendix B. In addition, "fuel" inputs are the primary variable costs associated with electricity generation. For wind power production, fixed costs are high, but low variable costs play to its competitive advantage against fossil fuel combustion systems. As discussed in Section I, uncertainty in fossil fuel reserves foster volatility in the prices of fuels; certainty in the future prices of resources like wind allow for clearer assessment of financing options which, in tandem with decreased manufacturing costs of technological components, will be important factors in bringing projects to fruition within the time frames set by domestic and international agreements.

[12] GWEC, *Global Wind Energy Outlook 2010*.
[13] National Renewable Energy Laboratory, "Large-Scale Offshore Wind Power in the United States: ASSESSMENT OF OPPORTUNITIES AND BARRIERS, September 2010.

Technical Limits to Implementation

Despite its proven potential to meet these goals, proposed high-capacity projects fail to reach completion in the US. Technical incapacity is not a frequent cause of project failure, but the difficulty of present-day grid integration will be helpful in assessing the impact of individual developments in the national electricity infrastructure on overall wind power incompatibility. Reaching the upper limitations of wind resource capacity will require further technological innovation to combat challenges associated mainly with transmission and distribution, or T&D. All forms of electricity distribution struggle with power storage, but the variability of the input resource in wind powered generation systems and the tendency for farms to be located at sites distantly located from potential users make efficient transmission systems a necessity. However, the structure and capacity of transmission in the US is unsuitable for wind power's quick and efficient distribution. While the development of the national energy infrastructure will be examined more closely in Part III, understanding the basics of the US grid construction is vital to addressing the technical limitations of wind power implementation.

"The grid," as it has been referred to previously, is actually the product of three individual but interconnected high-voltage networks. The low-voltage lines used by individual, unconnected suppliers of the early 20th century were replaced by interconnected transmission systems. Generators could be shared between utilities and less extra capacity had to be stored in case of sudden increases in demand. This cooperation and greater demand for electricity across vast distances increased utilities' need for efficiency; accordingly, higher voltage power lines were installed in three large interconnected systems. The outcomes of centralizing operational monitoring of these three systems are addressed in Section III. First, voluntary standards were developed by the electric utility industry to promote smooth operation of the interconnected system. As the operation grew, better coordination was required. As total demand increased, utilities also became susceptible to greater surges in momentary demand. To manage the bulk power systems and ensure the protection of the systems from foreign attack or disturbance, the electric power industry created the North American Electric Reliability Corporation (NAERC) and enlisted the help of two major national energy regulatory bodies to bolster reliability even further.[14] The interactions between the two bodies—the Federal Energy Regulatory Commission and the U.S. Department of Energy—and the industry will be given further consideration regarding how infrastructure development was affected.

Before proceeding, clarification of the terms "national energy infrastructure" or "national electricity infrastructure" is required. These terms are meant to refer to the host of equipment, operations, and inputs to electricity generation in the US. To be sure, no single structure underlies the entire nation's T&D system. Instead, utilities rely on three separately-functioning grids that cross state and national boundaries. The first serves the eastern half of the US, called the Eastern Interconnected System; the second provides T&D for areas between the Pacific Ocean and Rocky Mountain States, called the Western Interconnected System; the third serves areas around Texas including parts of Mexico, called the Texas Interconnected System.[15] An illustration of this system can be seen in Appendix C.

The costs associated with updating the electricity grid to meet a substantial portion of demand using wind energy are not yet low enough, or the perceived benefits not high enough,

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[14] United States Department of Energy Federal Energy Management Program (FEMP), "A Primer on Electric Utilities, Deregulation, and Restructuring of U.S. Electricity Markets 2002-05," May 2002, 4.0-5.0.
[15] US Energy Information Administration, "Electricity Explained," US EIA Website.

to spur investment. However, losses to T&D are substantial even in coal-fired generation systems. In order for electricity to reach its end user, power must be transported in large quantities over the electricity grid, power lines, and into homes or other spaces. The total output of a plant's generator does not reach end use. Losses vary in magnitude based on the age and efficiency of equipment in addition to the level of resistance in electrical wires. Normally, the grid and standard operating equipment for coal-fired plants lose 5% to 8% of total output during T&D. In a report published by the ABB Group, which manufactures energy distribution, total power lost to T&D in 2005 would have fetched nearly $19.5 billion on the commercial electricity market.[16] Adjusting these figures for 2010 data provided by the Energy Information Agency, average T&D losses of 7% totaled $33.7 billion.[17] Over time, these costs have become associated with the process, but underinvestment in transmission efficiency is costly.

Simply increasing the efficiency of electricity generation systems is not necessarily a path to sustainable development. The idea that improved efficiency increases consumption, often referred to as the "rebound effect," was related to coal-fired electricity generation by William Stanley Jevons in 1865. In his book *The Coal Question*, Jevons posited that the Britain, a rapidly-industrializing nation, was economically and politically vulnerable due to its reliance on easily-mined, depleting coal reserves. His theory, known as the Jevons Paradox, states:

> "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth. As a rule, new

[16] ABB, "Energy Efficiency in the Power Grid," 2007.
[17] U.S. Energy Information Administration. "Electricity Explained," US EIA Website.

> modes of economy will lead to an increase of consumption . . . Now, if the quantity of coal used in a blast furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each."[18]

Using fossil fuel resources with higher efficiency, then, could increase total consumption and fail to offset the high emissions output. In developing sustainable energy infrastructures and implementing new sources, efficiency gains and technological improvement need to be balanced with Jevons' cautionary theory.

Measures taken to reduce emissions from electricity generation, either through grid updates or innovations in storage and transportation of power, must be adaptable to diverse energy portfolios. Low-emission renewable energy sources are an option for maintaining similar levels of output by supplementing and, over time, replacing fossil fuel systems. At current technological status, wind-generated electricity is a feasible option for providing large loads of electricity under suitable conditions; however, wind technologies are used optimally as primary or complimentary producers in a larger system. Integration into diversified supply portfolios has been a key approach for the EU's dramatic increases in installed wind capacity. According to the European Wind Energy Association (EWEA), the size and inherent flexibility of the power system are crucial aspects in determining the system's ability to accommodate a high share of wind power. Due to its variable output according to conditions, systems using wind energy for heavy production should employ similar methods used to ensure fossil fuel-

[18] William Stanley Jevons, (1866) *The Coal Question: An Inquiry Concerning the Progress of the Nation and the Probable Exhaustion of our Coal-Mines*, 2nd edition, Macmillan, London: 1866, 123-125.

fired systems are capable of managing relatively random fluctuations in demand: system reserves and balancing methods serve as operational controls, allowing plant operators to adjust output based on need. The EWEA's standards for wind power integration are based on EU systems that provide a significant portion of demand using wind—around 20% of total demand—and that build in flexibility and diversify energy portfolios as total wind energy penetration increases.[19] In the US, increasing production from wind to similar levels of EU systems, then, should be addressed on a system-to-system basis, mixing sources according to availabilities in different geographical locations.

The technological status of the current electricity grid prohibits introduction of wind energy technologies. In exploring reasons for persistence of coal-fired electricity as the primary supply, consideration must be given to the historical development of the energy infrastructure as a whole. The modern grid was designed based on the use of coal-fired plants, the source of electricity for the earliest electrified cities, and hydroelectric power, which was used to bring electricity to rural areas. The development of these two vital systems facilitated the electrification of the US throughout the twentieth century, linking power plants, homes, and offices with an elaborate network of wires and equipment. Coal emerged as the primary fuel for supplying electricity into the 21st century, limiting the entrance of wind energy through technical specificity—fossil fuel plants convert chemical energy to electricity, while wind technologies converts kinetic energy to electricity, leading to inherent transmission system incompatibilities. However, the development of coal-burning capacity and its persistence have also been interpreted using theories of technological change accounting for social factors that contribute to the system's "momentum." In the next section, the theories are used to show how

[19] European Wind Energy Association, "Powering Europe: wind energy and the electricity grid." A Report by the European Wind Energy Association, November 2010.

wind energy integration confronts societal expectations of national energy infrastructure development that resulted from the rapid electrification of the US in the twentieth century.

Section III. History of the National Energy Infrastructure-Wind Energy Incompatibility

Defining the Sociotechnical System

Coal-fired electricity generation systems achieved widespread implementation and endured largely by satisfying local, regional, national, and international developmental goals. The development of wind energy systems, then, can be compared to the trajectory of the US energy infrastructure. This infrastructure, in its current form, can be considered a single, large technical system (LTS), one that encompasses generation and distribution technologies, suppliers, consumers, and institutions involved in the development and implementation of generation processes. Both developers and users increased the pace of the system's growth while implementation simultaneously influencing political, social, and economic dynamics in the US. As stated by historian Thomas P. Hughes in his seminal analysis of LTS, "they are both socially constructed and society shaping."[20] His analysis is important to the understanding of electricity generation systems' resistance to change. The US energy infrastructure is a "sociotechnical system," one that has distinct goals yet is also directed by the interactions of the individuals, technologies, and groups that are invested in its development. These interactions can be instrumental in a system's persistence, as Hughes relates to electricity systems: "Men and institutions developed characteristics that suited them to the characteristics of the technology. And the systematic interaction of men, ideas, and institutions, both technical and nontechnical, led to the development of a supersystem—a sociotechnical one—with mass movement and direction. An apt metaphor for this movement is

[20] Thomas P. Hughes, *The Evolution of Large Technical Systems*, p.1

'momentum.'"[21] Focusing on the aspects of coal-fired electricity generation systems' development that provided the "momentum" and staying power are vital to addressing the failure of sustainability metrics in promoting the growth of wind energy technologies.

Integrating wind power into the US electricity supply is restricted by a complex interaction of political, social, and economic forces that relate to the historical evolution of the current system. The development of the coal-fired system should be an important consideration in designing methods and measures of sustainable development. Hughes pinpoints four stages of "system evolution"[22] to address an otherwise complex development of the electricity generation system: invention and development, transfer from one region or society to another, system growth, and increased momentum. Contextualizing wind power within these stages to identify how each ushered in long-standing human-energy relationships can be useful in addressing barriers to implementation at the national level.

Invention and Development: Origins of Electricity, 1800s

The electrification of American cities in the late nineteenth century drastically altered American societal perception of the human-energy relationship. But the role of electricity within this human-energy dynamic can be traced to earlier stages of development. The first half of the nineteenth century, natural philosophers were building on the increased study of electric charge, light, heat, and motion by investigating how these forces of nature could be transformed from one to another. In industrializing nations, the scientific community turned much of its attention to work—how to harness nature to produce useable force and motion,

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[21] Hughes, *Networks of Power: Electrification in Western Society, 1880–1930*. Baltimore: Johns Hopkins University Press, 1983, p.140.

[22] Hughes, *Networks of Power*, p. 14

critical to manufacturing processes.[23] The development of theories regarding the conversion of heat and electromagnetic forces to motion facilitated profitable invention of electricity generation and distribution technologies later in the century. Prominent early developers formulated their theories relating to their philosophical schools of thought, which influenced how these technologies impacted society. Two of the most influential theorists, Sadi Carnot and Hans Christian Oersted, provided explanations of the conversion of heat to motion and the relationship between magnetism and electricity. Both would be essential to later inventions of electricity generation and distribution technologies by Thomas Edison, the inventor Hughes uses as a starting point for his four stages of development.

Carnot sought to explain how steam engines, vital tools to early industrialization manufacturing processes, converted caloric to motion. He explained this as a transfer of the caloric from one part of the steam engine to another, beginning in the furnace and transferring from the steam to cool water. He placed his focus on the temperature change of the caloric from hot to cold, not from one state to another. This concept allowed Carnot to observe that the caloric is actually conserved rather than consumed, with temperature change being the driver. According to Carnot, heat is the “immense reservoir” of nature’s economy, an idea that would manifest itself in the design of heat engines with increasing efficiency throughout the nineteenth century.[24]

Oersted discovered the link between electricity and magnetism in 1820 in an experiment using a magnetized needle and copper wire with electricity flowing through it. In this experiment, he hoped to prove yet another link between natural forces that would attest to his Romantic *naturphilosophie*. This philosophy held that an underlying force drove all others

[23] P.J. Bowler and I.R. Morus, *Making Modern Science: A Historical Survey*, p.81
[24] Bowler and Morus, *Making Modern Science*, 86-87

and that a fundamental unity exists between everything in nature.[25] In examining electricity and magnetism in this context, Oersted planted the ideas necessary for later conversions of this force to useful work.

Carnot and Oersted's discoveries would be influential in understanding both the conversion and conservation of energy and thus play a major role in defining the human-energy relationship They would also provide the foundation for the development of an American system largely dependent on heat engine-based generation. The convergence of ideas about converting, rather than consuming, fuel in producing useable energy during a time of rapid industrialization shaped how Americans came to understand the human-energy relationship. Economic and social growth during industrialization was facilitated by an "immense reservoir" of heat sources, unbridled by discovering the impossibility of consumption. Massively transmitting this power would rely on the technological implementation of Oersted's discovery of the link between electricity and magnetism. Just as his *naturphilosophie*-based theory proposed an underlying unity of natural forces, electrification later served as a link between US regions and thus portrayed electricity as a means of promoting connectivity.

Integrating wind energy into the electricity system challenges the model instilled by the convergence of ideas about the conversion, conservation, and use of natural forces. While climatic forces are largely based on the sun's radiation (heat), wind powered electricity generation systems use the wind's kinetic energy to turn turbines and produce electricity. This is a fundamental difference from fossil fuel combustion, which uses the heat produced by burning coal or another fuel to power turbines with steam. By removing combustion from the

[25] Bowler and Morus, *Making Modern Science*, 83

process, wind energy systems fail to fit the perception of nature as a heat source for human growth. In essence, wind energy is limited by a "mystique" similar to the one explained by Carnot's observation of the caloric changing temperature throughout the steam engine process.

Implementing wind energy sources also confronts the standard definition of "conservation" established in the early stages of system development. Whereas the discovery that energy cannot be consumed, but rather converted from one source to another, promoted widespread use of the heat engine, wind energy is often perceived as a technology that requires reducing consumption. The electricity grid has been built to handle bulk loads from fossil fuel generation, but struggles with the intermittent power levels produced by wind turbines. While grid incompatibility is a technical issue, this serves as an example of the technology shaping public opinion and society shaping technology. The system is built to harness the conservation of energy by a series of temperature changes using solid fuels in measured capacities. Wind energy, however, challenges utilities and users to reduce energy usage overall.

In addition to its impact on conservation, wind resource availability is highly localized and not easily transportable. The current system distributes electricity from centralized locations and can be carried great distances, so areas with few renewable resources benefit from this unification. Wind's incompatibility with this aspect of energy usage is best addressed through an assessment of the second stage of technical evolution.

Technology Transfer and System Growth: Centralization, Rural Electrification, and High Modernism

Cities were the first to benefit from US electrification initiatives owing to their high concentration of residents and industrial activity. Coal-fired generation systems are often found on the edges of cities, producing electricity and distributing it across a given geographical range. The establishment of high-voltage transmission lines—the first of which was built by American Gas & Electric in 1917—allowed cities to be powered by large plants located on the edge of town, often near rivers, rail stations, or, in many early cases, at the site of the coal mine.[26] These technologies were transferred to rural areas of the US, facilitating broader expansion of coal-fired systems. Perhaps the best example of the industrial era's impact on societal expectations of energy infrastructure development was the creation and implementation of the Rural Electrification Act. Engineer Morris Cooke had been drafting ideas and plans for rural electrification of the U.S. during his time in the offices of Pennsylvania mayors and governors in the 1920s, applying technical knowledge gained at Lehigh University in 1895. However, a convergence of ideas would bring the plan to full fruition. With the technical capacity reached, effective methods of centralized planning and construction were needed. The system's trajectory was largely influenced by the rise of scientific management during this era.[27] Scientific management is the application of scientific methods—observation, data collection, and technical interventions, for example—to the administration of a project or occupation. This form of management was growing in industrial America, largely due to the work of Frederick Taylor, also an engineer, who became a consultant to many large industries and promoted industrial efficiency.[28]

The spread of Taylor's ideas into industry helped Cooke navigate the complex economic and logistical task of providing power to rural communities and expand a consumer culture that was previously confined to cities. Cooke was appointed the administrator of the Rural Electrification Administration under Franklin Delano Roosevelt in 1935. He effectively

[26]Hunter and Bryant, *The Transmission of Power*, 148-215.
[27]Hindy Lauer-Schachter, *Frederick Taylor and the Public Administration Community: A Reevaluation.* Albany: State University of New York Press, 1989, 75-78.
[28]Lauer-Schachter, *Frederick Taylor,* 80-90.

leveraged the industrial movement of scientific management to create a technical plan for government implementation, brining coal-fired electricity to millions of farms and homes by the middle of the 20th century.[29] However, reaching this goal required managing other aspects of the project that might limit growth. Hughes recognizes these as "reverse salients" and proposes that successful system evolution depends on developers managing potential problems.[30]

Financing the project was one potential limitation even after projects were underway. The growth of the sociotechnical system around coal-fired electricity generation was concentrated in "large, centralized" generation sources—companies that were largely vertically integrated, owning mines, generating equipment, transmission lines, and other infrastructural technologies associated with large-scale electricity distribution.[31] The expansion of education in energy engineering—developing schools and programs producing innovative findings in the science of electricity generation and transmission—was tied directly to the rise of fossil fuel electricity production in the U.S. As Hughes notes, the system's construction relied heavily on a merger of interests: "The professors teaching the courses may be regular consultants of utilities and electrical manufacturing firms; the alumni of the engineering schools may have become engineers and managers in the firms; and managers and engineers from the firm may sit on the governing boards of engineering schools."[32] Invested stakeholders were distributed across the sectors of the system's development.

[29]Hughes, *Networks of Power*, 145.
[30] Hughes, *Networks of Power*, 79.
[31]Louis C. Hunter and Lynwood Bryant, *A History of Industrial Power in the U.S., 1780–1930: Vol. 3: The Transmission of Power*. Boston: The MIT Press, 1991, 148-152.
[32]Thomas P. Hughes, "The Evolution of Large Technological Systems," in *The Political Economy of Science, Technology, and Innovation*, ed. Ben Martin and Paul Nightingale. Northampton, MA: Edward Elgar, 2000, 288.

A growing consumer culture in the industrial US was driving the interests of each group involved in the development of the electricity infrastructure. The centrally planned electrification projects promoted and benefitted from greater production of consumer goods, often by the same companies that were providing electricity. This growing interest in consumer goods, and the technical capacity to use them, contributed to a drastic rise in electrified homes in the US. In 1910, one in seven American homes had electricity. By 1920, seven in ten had AC current available.[33] Companies took a hands-on approach to enlarging the consumer base. By personally engaging with customers through door-to-door selling, the Denver Gas & Electric Company in Denver, Colorado sold over 9,000 new irons to households in two years. [34]

A growing social demand for "high modernism" and consumer goods fueled the growth of electricity generation systems. In Table 2, the consumption of electricity by electrical appliances in the home can be seen in relation to the emissions and cost of each.

[33] Regina Lee Blaszczyk, *American Consumer Society, 1865-2005: From Hearth to HDTV*, 140.

[34] Blaszczyk, *American Consumer Society*, 140

Table 2: Energy Consumption in the Home

Electric Energy Consumption in the Home

Use	kWh/yr	$/yr[a]	CO_2 Emissions, lb/yr[b]
Air conditioner (room)	1,070	86	2,140
Air conditioner (central)	3,230	258	6,460
Coffee maker	100	8	200
Clothes dryer	1,060	85	2,120
Clothes washer (incl. hot water)	1,080	86	2,160
Dishwasher (incl. hot water)	935	75	1,870
Electric blanket	120	10	240
Furnace fan	600	48	1,200
Home computer	130	10	260
Lighting	844	68	1,688
Microwave oven	220	18	440
Kitchen range	840	67	1,680
Refrigerator	1,300	104	2,600
Stereo and radio	75	6	150
Television	197	16	394
Television, turned off	33	3	66
Toaster oven	50	4	100
Vacuum cleaner	25	2	50
VCR	40	3	80
Waterbed	960	77	1,920
Water heater	5,300	424	10,600
Water heater (standby losses)	795	63	1,590

[a] Based on $0.08/kWh.
[b] Based on 2 lb CO_2/kWh.
Source: Adapted partially from *Homemade Money—How to save Energy and Dollars in Your Home.* Richard Heede and staff of the Rocky Mountain Institute. Amherst, NH: Brick House Publishing Company, 1995.

Source: Blaszczyk, American Consumer Society

Section IV. A Note on Local Community Opposition to Major Wind Projects

The fervor for access to electricity increased the rate of investment and construction of necessary infrastructure. In contrast, recent wind energy development in the US has been hindered by fervor *against* major projects in many regions of the country. Economic concerns are often voiced by local industries concerned by the threat farms may pose to their access to resources. Environmental groups eschew the projects based on threats to the local marine ecosystem. Social concerns are also recurring points of protest among citizens worried about how development will affect a host of factors ranging from housing values to the local culture; these points are often tied to the economic and environmental concerns of other groups by local politicians vying for their constituencies in approval and permitting processes. But rejection of offshore wind farms by local communities is not merely a result of dollars and cents added to electric bills, effects on local fish populations, or visual pollution on beachfront properties; rather, cultural perspectives on the relationships between humans, resources, and electricity production are embedded in the natural history of each area and shaped by the historical trajectory of electricity generation system development in the US.

Planning and implementation of wind energy projects require careful attention to land use practices, visual and auditory externalities, and methods of electricity transmission. The following study examines a failed Massachusetts offshore wind power project, which had the technical and financial viability to reach completion but threatened to alter the established relationship between the region's people, their surrounding ecosystem, resource consumption traditions.

Section V. Case Study: The Cape Wind Project

Five miles from the shore of Mashpee, Cape Cod, powerful winds ripple the surface of shallow water over Horseshoe Shoal. A 26 square mile area of the shoal, nestled between ferry routes from the mainland to Nantucket and larger shipping channels, is the proposed site for construction of the first offshore wind farm in the United States. Eight years and countless political and legal processes after its initial proposal, the Cape Wind Project obtained all of the necessary permits from local and federal agencies. However, none of the proposed 130 horizontal-axis wind turbines had been installed on Horseshoe Shoal by 2011. The initial project planned for a peak generation capacity of 454 megawatts (MW), enough to power 420,000 homes and about 75% of the average electricity demand for Cape Cod, Martha's Vineyard, and Nantucket island combined region. In addition, the estimated carbon dioxide emissions offset was near a million tons per year and the power had the potential to replace 113 million US gallons of oil annually—a drastic local change, as about 45% of the Cape region's electricity is produced at the Canal Power Plant, which uses bunker oil and natural gas as its primary combustion fuels. [35] Each of these outcomes is an advancement of national and global environmental sustainability goals, ensuring energy security while reducing atmospheric pollution.

Natural History, Ecosystem Protection, and the Human-Nature Relationship

The role of the marine ecosystem in supporting Cape Cod's communities is entrenched in the natural and human history of the Massachusetts coast. As early as 6,000 BCE, the first small Native Americans settlements harnessed the ecological productivity of the waters to

[35] Cape Wind Project, Article 37.

survive the otherwise infertile and harsh terrestrial niche.[36] Rising sea levels and climate patterns inundated the area with ponds, estuaries, salt marshes, and a diverse set of marine species. Regular fish runs and improved methods of harvesting the ocean's resources ensured the survival sedentary civilizations and, by the time of their contact with Europeans in 16th century, the Wampanoag had sustainably populated the Sound's coastal margins and estuaries. Without arable land available for agricultural production, settlers occupied the margin between land and sea; their survival depended on their ability to draw upon both. The complex task of sustaining an "estuarine sedentary" civilization required increased social hierarchy and political centralization.[37]

Although European contact would transform the demographics of the Cape Cod area, Native American methods of thriving under unique ecological conditions were transferred to 17th century settlers of the Cape Cod region. As Hughes explained, the transfer of technological systems occurs in several stages. The first is the stage of technical development; in this case, the early Native American settlers developed a system that incorporated marine and terrestrial ecosystem advantages in populating the area. The second stage is the transfer of technological systems from the region or society that developed it to others. Natives' efficient techniques and useful tools for fishing, planting, and managing the few resources that were available on the mainland were adapted to the purposes of early New Englanders. "Life on the margin" required delegation of responsibilities to maximize efficiency and maintain the sensitive ecological balance. The tasks of extracting food from the ocean to meet dietary needs, managing terrestrial forests and other sources of energy for sustained practical use, and

[36] Matthew McKenzie, *Clearing the Coastline: The Nineteenth-Century Ecological & Cultural Transformation of Cape Cod*. Hanover: University Press of New England, 2010, 16
[37]McKenzie, *Clearing the Coastline*, 12-13.

ensuring the proper allocation of resources were drivers of social stratification. This began the third stage of Hughes' model for technological transfer, as European settlers progressively improved fishing technologies and resource extraction through political centralization and social hierarchy based on occupation.[38] Hughes posited that technological systems achieve desired outcomes through "reciprocal and interdependent cause and effect processes" that balance the role of social and technical forces in developmental stages.[39]

Geopolitical Obstacles and the Impact of Cultural Values on Methods of Ecological Protection

The transfer of Native American methods of surviving in the Nantucket Sound region was an integral component of ensuing economic and social development. The regional culture, reflective of this long-standing communal dependence on the waters' resources, is defined by a sense of ownership and paternalistic responsibility over Nantucket Sound. As a result, citizens are politically and economically active in ensuring that the marine ecosystems are protected from potential exploitation and harms. Proposals to open the waters to industrial uses are met with opposition from community groups challenging each project's environmental, economic, and social sustainability. Fierce opposition limits the ability of companies and organizations to harness the Sound's resources in financially and technically feasible ways. This type of activism, based on economic and cultural ties to the area's resources, illustrates the influence of social structures on the process of technological change.

In evaluating the reasons behind opposition to the wind farm, careful consideration must be given to the history of the region's energy infrastructure and pattern of economic growth. While the aforementioned environmental groups assert that the Cape Wind Project

[38] McKenzie, *Clearing the Coastline,* 16-23.
[39] Hughes, "The Evolution of Large Technical Systems."

threatens the Sound's sensitive ecosystem, the current form of electricity generation has taken a toll of its own. Both the Canal Power Plant and Cape Cod Power Plant receive shipments of oil requiring travel through the Sound. The latter example uses oil as its feedstock and transportation accidents have led to two major oil spills—one in 1976 (about 8 million US gallons) and another in 2003 (about 100 thousand US gallons). The spill killed hundreds of birds and shut down 100,000 acres of shell fishing beds.[40] Oil spills have disturbed the local environment as well as the fishing industry on multiple occasions—two outcomes that are proven results oil dependence for electricity generation and yet form the basis of opposition to the offshore wind farm.

[40] Cape Wind, Article 37.

Section V. Future Outlook

Given the current reliance on imported and domestic fossil fuels in the US, expansion of renewable energy projects has been a priority across industries. In particular, solar energy has benefitted from substantial government rebate programs, private financing and investment, and its "off-the-grid" capabilities. Transportation technologies, ranging plug-in hybrids to fuel cell systems, have gained momentum from stricter emissions and fuel efficiency standards as well as cultural inertia from automakers' marketing campaigns and the growing sustainability movement. Solar and transportation technologies are currently benefitting from technological momentum that closely parallels the forces that led to the construction of sociotechnical system around coal and natural gas-fired electricity generation systems. Many of the innovative institutions, social conditions, and technologies that arose around coal-fired generation are applicable to these technologies, yet do not drive the integration of wind power into the American energy landscape.

Today, the global economy is heavily influenced by fossil fuel prices and their direction, attesting to coal-fired electricity generation's seamless integration into the American economic and social structure.[41] Coal's weight can be calculated, ownership of mines is definable by land and property rights, it can be transported by boat, rail, or truck, and the costs of mining and transporting are related to the efficiency of related technologies. Because wind is a natural (and invisible) force, predicted only by changing patterns and forecasts, building a sociotechnical system around it has proved difficult. Companies innovate based on

[41]Martin V. Melosi, *Coping with Abundance: Energy and Environment in Industrial America 1820–1980*. Philadelphia: Temple University Press, 1985, 130-210.

technologies to harness the wind, such as turbines and windmills, yet cannot sell and trade the source itself because ownership is limited to the use of the land. The industry has less of a propensity for vertical integration, which was a vital outcome of coal commodification and key to its success as a source of electricity generation.

While environmental historians and historians of technology have established the historically-built strength of fossil fuel sociotechnical systems, many have also theorized about a similar connection to renewable sources. Perhaps the most compelling example of this is Richard White's description of the Columbia River in *The Organic Machine.* White's historical narrative profiles the changing community built around the river and its hydroelectric dam. While White devotes a considerable portion of the text to detailing the impacts of dams and fisheries on the river itself, his most meaningful points reach beyond the intricacies and particularities of harnessing the Columbia for energy and livelihood. He theorizes that humans have come to know nature through "work," in both the practical and scientific senses of the word—a relationship that continually changes with the conditions of the environment and society. The result is the view of the river as an "organic machine," one that harnesses natural moving forces for the increased productivity and sustainability of human life. White defines the role of humans in a system of energy, work, and technology though a narrative about how harnessing natural sources alters the states of human society and the surrounding environment.[42] Such studies can be important guides to building green economies and restructuring infrastructure to address the changing human-energy relationship.

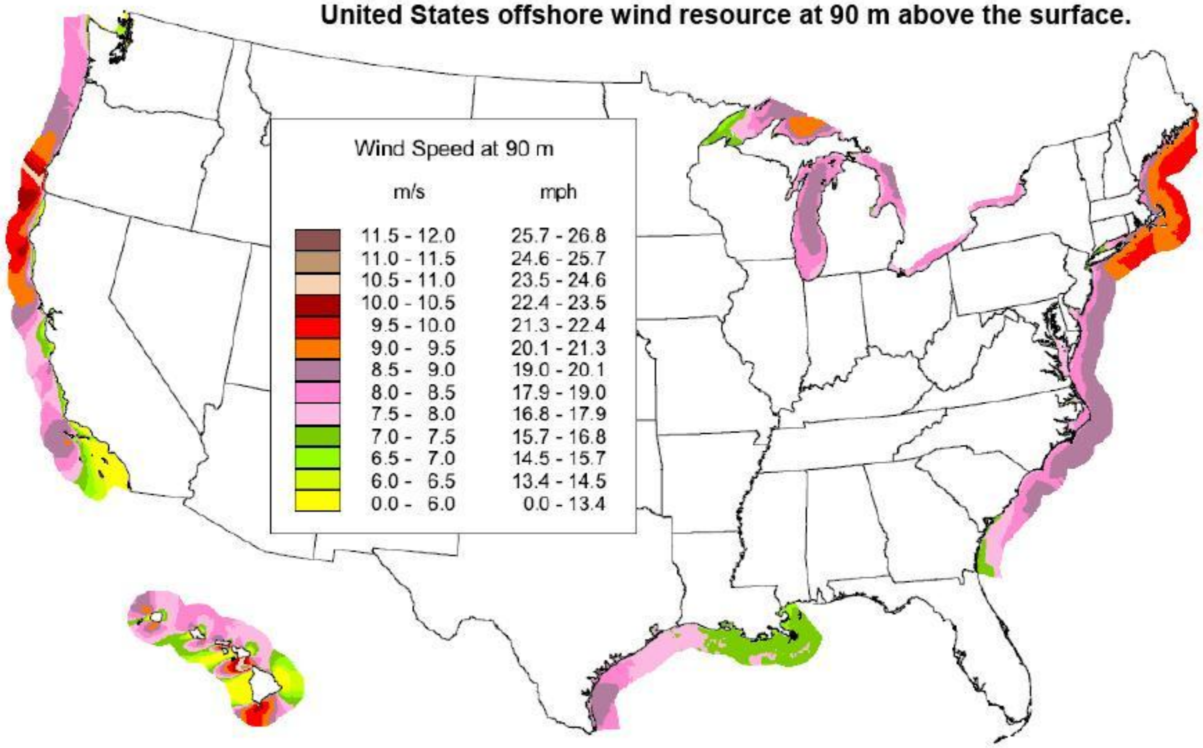
[42]Richard White, *The Organic Machine: The Remaking of the Columbia River*. New York: Hill and Wang, 1996.

Appendix A: Greenhouse Gas Data

GREENHOUSE GASES					
Gas	Sources	U.S. Emissions (MT/yr)	GWP*	Atmospheric Lifetime	2003 Concentration
CO_2	Fossil fuels, deforestation	5500	1	100 years	373 ppM
Methane	Rice fields, cattle, landfills	600	21	12 years	1.7 ppM
***GWP = Global Warming Potential, which is related to a molecule's ability to absorb thermal radiation relative to that of CO_2** **Source: Intergovernmental Panel on Climate Change**					

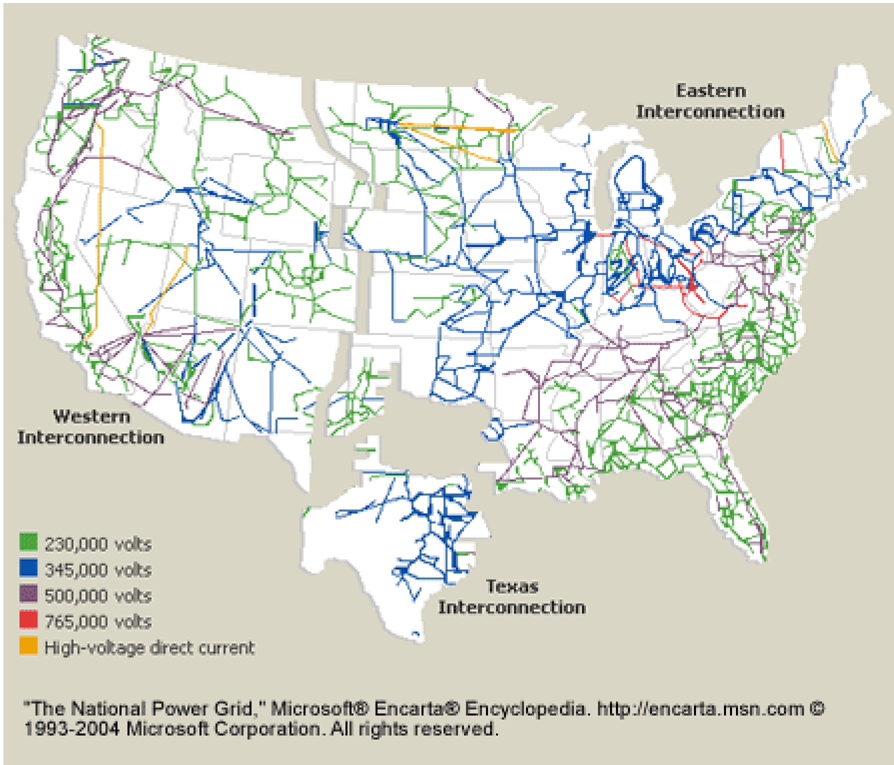
Source: Hinrichs & Kleinbach, Energy: Its Use and the Environment, 290-293.

Appendix B: Offshore Wind Capacity Map, United States



Source: NREL

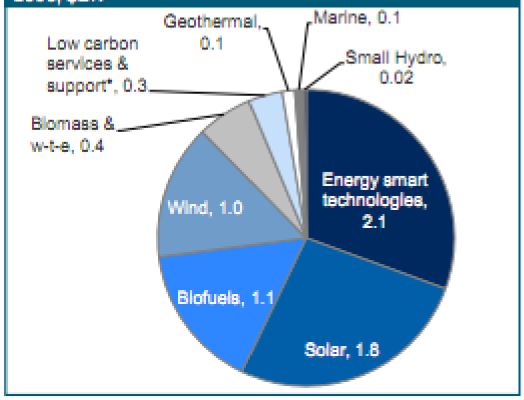
Appendix C: National Power Grid



Source: U.S. Energy Information Administration

Appendix D: Investment in Wind Energy

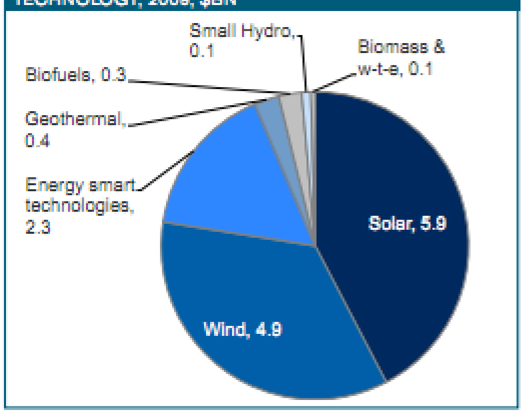
FIGURE 10: VC/PE NEW INVESTMENT BY TECHNOLOGY, 2009, $BN



VC/PE new investment excludes PE buy-outs. Total values include estimates for undisclosed deals. * Includes CCS

Source: Bloomberg New Energy Finance, UNEP SEFI

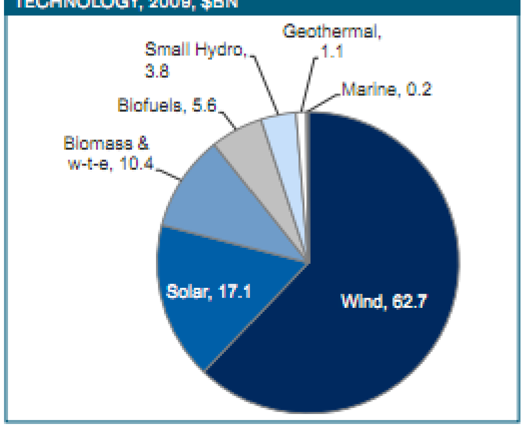
FIGURE 11: PUBLIC MARKETS NEW INVESTMENT BY TECHNOLOGY, 2009, $BN



* Includes CCS

Source: Bloomberg New Energy Finance, UNEP SEFI

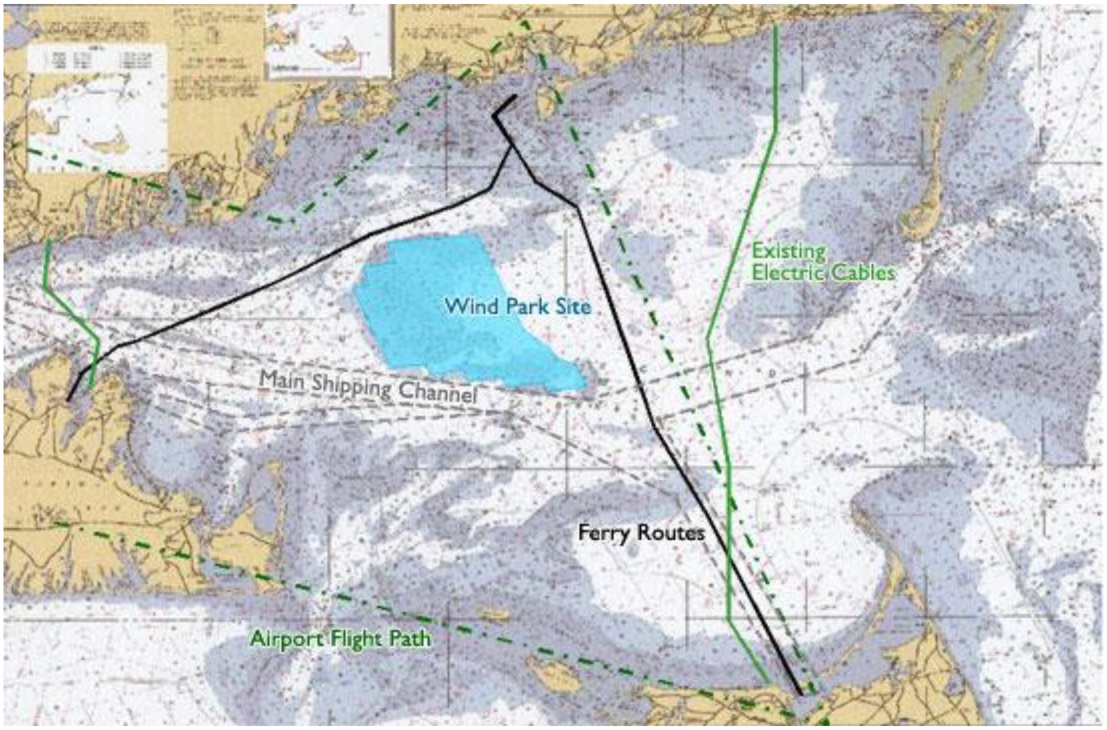
FIGURE 12: ASSET FINANCE NEW BUILD BY TECHNOLOGY, 2009, $BN



Total values include estimates for undisclosed deals

Source: Bloomberg New Energy Finance, UNEP SEFI

Appendix E: Map of Horseshoe Shoal and Cape Wind Project Site



Coordinates: 41.542°N 70.321°W

Source: Cape Wind Website

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