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A Preliminary Benefit-Cost Study of a Sandia Wind Farm

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Abstract

In response to federal mandates and incentives for renewable energy, Sandia National Laboratories conducted a feasibility study of installing an on-site wind farm on Sandia National Laboratories and Kirtland Air Force Base property. This report describes this preliminary analysis of the costs and benefits of installing and operating a 15-turbine, 30-MW-capacity wind farm that delivers an estimated 16 percent of 2010 onsite demand. The report first describes market and non-market economic costs and benefits associated with operating a wind farm, and then uses a standard life-cycle costing and benefit-cost framework to estimate the costs and benefits of a wind farm. Based on these “best-estimates” of costs and benefits and on factor, uncertainty and sensitivity analysis, the analysis results suggest that the benefits of a Sandia wind farm are greater than its costs. The analysis techniques used herein are applicable to the economic assessment of most if not all forms of renewable energy.

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1. Introduction

1.1. Mandates and Incentives for a Sandia Wind Farm

As outlined in Karlson (2009), there are currently a number of federal legislative and other incentives in place to encourage the use of renewable energy at site locations such as Sandia National Laboratories, including the Energy Policy Act of 2005, Executive Order 13423, the DOE/NNSA Order 430.2B, the DOE TEAM Initiative, and the Production Tax Credit. While many of these are based on federal mandates that are predominately environmental in nature, they also involve monetary taxes and incentives. Largely due to these mandates and incentives and system cost effectiveness, wind power has made significant inroads in the United States, as illustrated by Table 1.

Table 1. U.S. Wind-Power MW Capacity, by State and Year Online¹

STATE	2010	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
Texas	9727	9,403	7,113	4,353	2,736	1,992	1,290	1,290	1,096	1,096	184
Iowa	3670	3,604	2,791	1,273	932	836	634	472	423	324	242
California	2739	2,798	2,537	2,439	2,376	2,149	2,095	2,025	1,823	1,683	1,616
Oregon	2095	1,758	1,067	885	438	338	263	259	218	157	25
Washington	1964	1,849	1,375	1,163	818	390	241	244	228	180	0
Illinois	1848	1,547	915	699	107	107	51	50	0	0	0
Minnesota	1818	1,810	1,753	1,300	896	745	600	558	338	320	291
New York	1274	1,274	832	425	370	186	48	48	48	48	18
Colorado	1248	1,244	1,068	1,067	291	231	231	223	61	61	22
Indiana	1238	1,036	131	0	0	0	0	0	0	0	0
North Dakota	1222	1,203	714	345	178	98	66	66	5	0	0
Oklahoma	1130	1,031	708	689	535	475	176	176	0	0	0
Wyoming	1101	1,099	676	288	288	288	285	285	141	141	91
Kansas	1026	1,021	921	364	364	264	114	114	114	114	2
Pennsylvania	748	748	361	294	179	129	129	129	35	35	11
New Mexico	597	597	497	496	496	406	266	206	1	1	1
Missouri	457	309	163	62	0	0	0	0	0	0	0
Wisconsin	449	449	449	53	53	53	53	53	53	53	23
West Virginia	431	330	330	146	66	66	66	66	66	0	0
South Dakota	412	313	187	98	44	44	44	44	3	3	0
Montana	386	375	271	153	146	137	1	1	0	0	0
Utah	233	223	20	1	1	1	0	0	0	0	0
Maine	200	175	47	42	9	0	0	0	0	0	0
Idaho	164	147	76	75	75	75	0	0	0	0	0
Nebraska	153	153	117	72	73	73	14	14	14	3	3
Michigan	143	138	144	3	3	3	2	2	2	2	1
Arizona	63	63	0	0	0	0	0	0	0	0	0
Hawaii	63	63	63	63	42	9	9	9	9	2	2
Tennessee	29	29	29	29	29	29	29	2	2	2	2
New Hamp.	26	25	25	1	1	0	0	0	0	0	0
Massachusetts	17	15	6	5	4	1	1	1	1	1	0
Ohio	10	7	7	7	7	7	7	4	0	0	0
Alaska	9	9	4	2	2	1	1	1	1	1	1
New Jersey	8	8	8	8	8	8	0	0	0	0	0

In response to these mandates and incentives, Sandia National Laboratories conducted a preliminary study of the potential for a wind farm at the Sandia facilities on Kirtland Air Force Base (KAFB). As described in Karlson (2009), there are significant monetary costs and benefits associated with installing a wind farm, for many large power users and for Sandia in particular. This report expands this earlier analysis, by refining the estimates of life-cycle cost and benefit-cost, based on updated cost and power data and a standard life-

¹ Correspondence with Ben Karlson, February 14, 2011.

cycle costing framework applicable to many different types of renewable energy and its installations.

A typical life-cycle cost analysis and associated benefit-cost analysis involves: identifying potential costs and benefits, classifying them, estimating them, and then directly using them in calculations. Classifying costs and benefits into types helps ensure that particular items are not overlooked. Toward this end, there are at least two types of costs and benefits that can be captured analysis: *market-based* costs and benefits, or costs and benefits that are directly transacted in markets; and *non-market-based* costs and benefits, which are often indirectly transacted or transferred.

Wind energy is competing very effectively with combustion turbines, the (previously) least-cost source of U.S. electricity generation. Studies recently conducted for both the Eastern and Western interconnections find that system total system cost for meeting a specified load target is reduced when wind power displaces combustion turbine generated power (given that wind power is operationally feasible for the system). The conclusion of these studies and from actual operating wind farms is that wind is becoming competitive with other, more traditional, energy generation technologies, even solely based on its market (contractual) costs. When non-market costs and benefits of wind are included, it is even more cost effective. It is important to our analysis, then, that we fully understand the potential market and non-market costs and benefits of wind power.

1.2. Market-Based Costs and Benefits

Wind power and other renewable power technologies have inherent market-based costs and benefits, i.e., ones that are transacted through contracts and other financial means. Many if not all of them are often included in traditional energy economics analysis. These market-based costs and benefits include:

- Costs of installing and operating current and new energy generation technologies, from coal, gas, petroleum, geothermal, wind, solar, and other sources;
- The costs of paying for or receiving credits for electric power from a mix of power sources and uses, including the different market prices and power consumption levels associated with these different power sources/uses; and
- Government-enacted regulations, taxes, premiums, cap-and-trade policies, and other means of influencing the generation, transport, and end-use of electric power.

Inherent to this type of traditional analysis is the notion of an owner, stakeholder, or decision maker who must make purchasing/payment decisions over a *study period*, or fixed period of financial concern. The economic analysis is analogous financial decisions regarding the balance of payments or income/expense sheet over the useful life of the particular structure(s), investment(s), or asset(s).

1.3. Non-Market Costs and Benefits

In addition to market-based effects, wind-power-related activities generate costs and benefits beyond its purely transactional or market costs and benefits. Even the provision

of the basic elements of shelter, food, and clothing generate non-market effects — economic benefits or costs to transacting parties that are not included in the price of particular good or service traded. It isn't surprising then that wind power production — as with all forms of energy production — generate non-market costs and benefits.

What is a non-market effect? In our economic system most goods and services are traded in markets through the use of money, near-money, or credit. In theory, the price, more strictly the *marginal price*, of a good or service is thought to cover all of the supplier's costs of providing that good or service. Furthermore, to the purchaser of that good or service it's marginal price theoretically reflects all the value (benefit) the purchaser receives from owning or consuming that good or service.

In practice, however, this is rarely the case. Take a well-known example of a bee-keeper whose bees pollinate a farmer's fields. The farmer doesn't pay the bee-keeper for the services of the bees and the bee-keeper doesn't pay the farmer for the services of his fields in providing flowering plants for the bees to make honey. There is a two-way flow of benefits from these two economic "actors" that does transact through a market.² Many examples of these *externalities* exist in economics. Non-market effects can be either positive or negative depending upon whether they confer benefits or costs on individuals outside of those who participate in the economic activity generating the externality.

Why should we be concerned about non-market effects? From an economist's standpoint, they signal the possibility that the relative production of different goods and services may be out of balance, in so far as society at large is concerned. Pollution is an often-cited source of non-market effects. If a production process uses a publicly accessible lake for disposal of its polluting waste products without paying for its use of the water, others also using that lake may be required to clean the water (at their cost) or suffer damage as a result of the pollution. If, on the other hand, the producer using the lake had to clean its waste stream, these cleanup costs would be included in the marginal price of the product it manufactures, the product would be more expensive, and sales would be lower.³

Frequently external effects occur over time. For example, *life-cycle cost analysis* (LCCA) demonstrates that the disposal of long-lived goods can be costly and that such disposal costs are typically not considered in production or consumption decisions. Even for consumption goods, it can be observed from weekly curb-side trash pickup that packaging materials usually end up in the city landfill, whose costs are covered largely through some form of taxation; neither producers nor consumers consider this in their production and consumption decisions. The key insight from life-cycle cost analysis is the application of a "cradle-to-grave" costing of the material costs (including externalities), manufacturing costs (including externalities), operation and maintenance costs (including externalities) and demolition and disposal costs.

LCCA is used for both project-level studies, such as the decision to build a wind farm at Sandia, or for strategic studies, such as whether to develop a particular new energy technology. For strategic studies, LCCA is a comprehensive means of assessing all of the

² Note that if the bee-keeper and the farmer are one and the same, the external benefits that each obtain from the activities of the bees are internalized. Ownership can internalize otherwise external effects.

³ In the language of economics we would say that demand curves slope downward and less of the product is purchased when its price is higher.

costs and benefits of an energy technology. Figure 1 presents a schematic of how “cradle to grave” LCCA is typically performed for strategic studies of energy technologies.

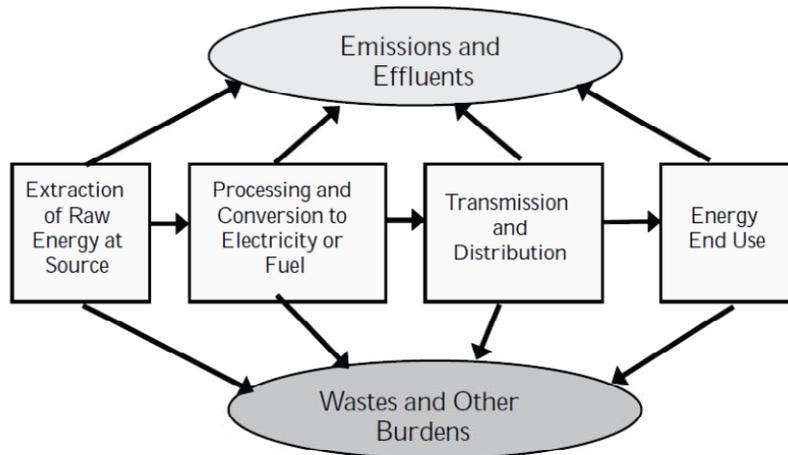


Figure 1. Life-cycle Cost Analysis Process for Energy Technologies⁴

At each box in Figure 1, for a given energy technology under consideration, the analyst conducts a process that:

1. Estimates burdens that flow through media — air, water, soil to affect people, the environment, the built environment;
2. Estimates ambient concentrations in media;
3. Estimates exposure to pollutants;
4. Estimates effects or impacts — the health consequences of the exposures;
5. Estimates damages — the value to society of avoiding these impacts.

Many if not all of these costs and benefits are non-market in nature, i.e., they are not captured in a market or contractual economic relationship.

1.3.1. Relative Importance of Non-Market Effects

While wind power is catching on in the U.S., European Countries, particularly Germany and Spain, are quite advanced in technological development and deployment of wind power. China, as well, is making major investments in wind and solar energy technology development, commercialization, and deployment. As a result, studies of the economics of wind power are more common in Europe.⁵ As one example, Figure 2 displays results from one report on the relative magnitudes of market costs (listed as “internal costs” in the figure) and non-market costs (“external costs”) for wind and conventional electricity.⁶

⁴ National Academy of Sciences, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, accessed at <http://www.nap.edu/catalog/12794.html> on December 21, 2010.

⁵ This may also have something to do with the structure of the electrical utility industry in Europe as compared with the United States.

⁶ *Conventional energy* refers to electricity-generation technologies that, through their repeated deployment by the industry, have become customary. These include coal, oil, and gas for either direct combustion or the raising of steam, nuclear-steam, and hydro, including impoundment systems, run-of-river, and pumped storage.

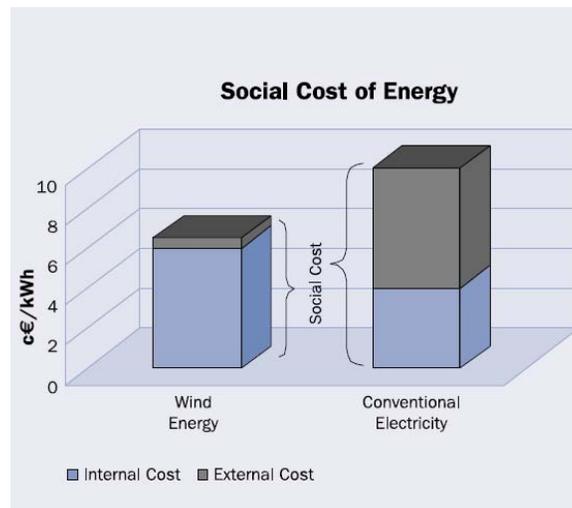


Figure 2. Cost of Wind Energy versus Conventional Energy, in Euros/kWh⁷

The figure suggests that the internal costs of wind energy are higher. When external costs are considered together with private costs, however, it suggests that wind is the more economical choice. While the data in Figure 1 are illustrative, they do reflect the general relationship between European wind and conventional energy costs.

Similar relationships exist for relative U.S. energy costs. Recent data, however, suggests that wind may be close to economically competitive with the otherwise least-cost energy source solely based on its market costs. Using Figure 1 as a discussion guide, conventional energy (the right column) in the U.S. is dominated by coal. The key reason for the large block of external costs for U.S. conventional energy is the air pollution caused by the burning of fossil fuels such as coal, predominately emissions of oxides sulfur and nitrogen that have negative human health effects and contribute to global climate change. Furthermore, the requirement to ship coal large distances from the point of mining to the point of use as a fuel contributes further to these two air quality effects.⁸ Generally it is the case that the non-market effects of the production of energy are negatives, by whatever technology the energy is produced, because they usually cause degradation of human health, natural ecosystems, and the built environment.

1.3.2. Potential External Benefits of Wind Energy Technology

Avoided Pollution/Health Costs

The main potential external benefits associated with wind energy are “avoided costs,” particularly avoided costs associated with green house gas emissions that would otherwise result from the burning of fossil fuels. As noted, air pollutants from fossil fuel burning, particularly from coal, have negative effects both on human health and on the

⁷ European Commission, Directorate-General on Energy, *Wind Energy: The Facts. Volume 4 – The Environment*.

⁸ This is the main argument that many proponents of nuclear power employ as a means to promote nuclear electricity generation technology—that it is relatively free of negative effects on air quality and global climate change. Such proponents neglect to point out that nuclear power has its own externality that may be more severe—the presence of large and growing quantities of highly radioactive spent fuel that requires storage, maintenance, and monitoring.

environment in their contribution to global climate altering effects of greenhouse gas emissions.⁹ Even with nuclear power, which also has the avoidance of emissions benefit advantage, there are large unavoidable external costs associated with the storage of spent nuclear fuel and the very small risk of large social cost due to an accident associated with a nuclear reactor excursion. The avoidance of air pollution is a strong argument in favor of wind power technology.

Reduced Water Consumption

Any electricity generation technology that either raises steam as a motive force to turn a turbine (nuclear) and/or burns fuel to generate the heat to raise steam (coal), or burns fossil fuel directly to turn a turbine (natural gas-fired combustion turbines) requires large quantities of water for cooling and/or in the steam cycle. This leads to large quantities of water consumption, which is becoming an increasing problem in the arid southwestern U.S. and other parts of the world. If global climate change increases the extent of arid areas of North America the problem of water acquisition could become a binding constraint for expansion of electricity generation technologies that rely on large quantities of water. Increasingly it is the case that power plants will not receive required permits by regulatory authorities unless the developers can demonstrate their access to sufficient quantity of water to operate the facility throughout its useful life. This is forcing developers to formally purchase water rights in emerging water markets throughout the western U.S., which puts power plant developers in direct competition with agricultural interests and municipalities all of whom are also endeavoring to secure reliable water supplies. The Albuquerque area, for example, is a water-scarce area. Implementing renewable energy on the Sandia site would contribute to lower water consumption for power production.

Lower Single-Target Threat

Another potential benefit that wind power provides is dispersal of generation capacity over a wider geographic area that results in a lower risk that the facility could become a target for terrorist activity. Dispersed wind facilities reduce the threat, vulnerability, and consequences of such activity and therefore reduce its likelihood increasing energy security.

Indirect Economic Impacts

Economic growth and development increases the demand for electricity and supplying that demand, by whatever technology, results in increased employment. Energy facilities involve a construction phase during which increased employment is readily evident and an operations phase that normally involves a fairly steady but lower level of employment. Conventional energy facilities by their nature (large size and output) typically involve more employment over a longer period of time than typical utility scale renewable energy projects. The types of jobs involved in conventional versus renewable energy projects can also be quite different. The operation and maintenance phase of conventional versus renewable projects can be quite different as well. Conventional energy facilities are normally larger in capacity and therefore will require more such employment. In addition, employment to produce the fuel (coal or natural gas) and transport it to the power plant site would be counted. Wind projects, once they are constructed, require somewhat less

⁹ The emergence of “cap and trade” programs and/or carbon taxes would have the effect of internalizing these otherwise external costs. However, to date such policy actions have not been politically possible in the United States.

operation and maintenance attention and therefore may require fewer employees. However, if one were to normalize capacity for a conventional and a wind energy project in or to compare the employment for equivalent capacity, it is unclear which would involve the larger employment impact. Clearly, however, since employment involves the expenditure of money on wages and salaries and other employment costs, the project type—conventional or renewable—that involves the lower employment will have a cost advantage. In the case of the Sandia wind farm project it can be stated unequivocally that implementation of the project would increase local employment in Albuquerque.

Effects of Unbundling and “Avoided Cost” Regulations on Calculating Benefits

The Public Utility Regulatory Policy Act (PURPA) of 1978 and the following FERC Orders 888 and 889 together provided a significant impetus to the introduction of renewable energy projects at the utility scale. These legislative and regulatory initiatives introduced the concept of “avoided cost” and defined a new category of investor in energy supply projects: independent power producers. The FERC orders enabled open access to the transmission grid and introduced the concept of unbundling — splitting the cost of delivered energy between generation, transmission, and distribution. States then began to adopt renewable portfolio standards (RPS) that required the state-regulated utilities to obtain a certain percentage of capacity in the form of renewable energy projects at some future assessment date. Most of the investment in utility-scale renewable energy projects that has occurred in the last several decades was completed by independent power producers applying the economic concept of “avoided cost” enhanced the viability of the project. New Mexico has a renewable portfolio standard and, in developing a wind power project, Sandia would be advancing the cause of PNM in achieving their RPS.

1.3.3. Potential External Costs of Wind Energy Technology¹⁰

Despite its relatively benign external impact (e.g., Figure 1), the production of wind energy does have some negative external costs, though these external costs are typically minor relative to other conventional energy technologies. The following are the most frequently mentioned external costs.

Visual Intrusion of the Turbines and associated Equipment in the Landscape

Wind velocities are normally higher where land is flatter and there are fewer vertical obstructions (trees, etc.). For this reason, wind farms are being constructed in the Great Plains of the Midwestern and Western United States. However, this tends to make the presence of wind farms much more visible, and some localities object to the sight of tall structures dotting the landscape. While wind farm planners are making efforts to reduce visual impacts, such impacts nevertheless remain.

Noise

Noise and disturbance is generated during the installation and operation of a wind turbine. The most significant concern is the aerodynamic noise generated by the turbine

¹⁰ For more information on external costs of wind energy see, Ladenburg, Jacob, *et al* “Economic Valuation of the Visual Externalities of Off-Shore Wind Farms,” Food and Resource Economic Institute Report Number 179. Copenhagen, DN 2005; and European Commission, Directorate-General on Energy, *Wind Energy: The Facts. Volume 4 – The Environment*.

blades, which is similar in sound to noise from wind blowing through trees. Modern wind turbines can be heard up to 300 meters away.

Impact on Birds

Birds colliding in flight with moving turbine blades and behavioral disturbance from blade avoidance are frequently cited. However, studies show that, in fact, birds rarely do collide with rotor blades.

Electromagnetic Interference

Radio waves and microwaves used for communication purposes can be affected by the moving rotor blades. However studies show that this is not a very frequent occurrence.

Impacts of Construction on Terrestrial Ecosystems

Construction and maintenance of wind farms cause long-term loss of wilderness land. However, this impact is thought to be minimal because only access roads and a small area of land on which the tower stands are actually lost. Agricultural activities, for example, can continue; in fact, farmers and ranchers are reported to be in favor of wind farms on their land because the lease revenue helps the financial viability of farms and ranches. This is in dramatic contrast to many other forms of natural resource development such as multi-purpose hydroelectric impoundment projects, surface, and even underground mining, and forestry. In these latter endeavors, the landscape is, for all intents and purposes, irretrievably altered.

Accidents

Industrial accidents are ubiquitous where large machinery and heavy equipment is operating. In a life-cycle context, accidents will occur in the manufacture and transport of components required to install the tower and other turbine equipment. The short accident record that exists indicates that most wind power accidents occur in construction and maintenance of the equipment.¹¹

1.3.4. Ranking Energy Technologies Based on External Costs

The National Academy of Sciences recently completed a study¹² in which life-cycle cost analysis was used to evaluate and quantify the external costs of the main energy technologies in use in the U.S. today. Their conclusions for each energy technology are summarized in this section.

Electricity from Coal

For electricity generation from coal study participants were able to monetize effects on human health, visibility of outdoor vistas, agriculture, forestry, and damages to building materials associated with emissions of airborne particulate matter, sulfur dioxide, and nitrogen oxide from coal-fired power plants in the United States. More than 90 percent of monetized damages are associated with premature human mortality, while 85 percent of damages come from sulfur dioxide emissions. Aggregate damages in 2005 were evaluated at \$62 billion or an average of 3.2 cents per kilowatt-hour, weighting each plant by the electricity it produces. When the plants were “binned” or grouped into deciles based on their aggregate damages, it became clear that a small number of plants were

¹¹ ECU, *Wind Energy: The Facts, Volume 4 – The Environment*, p. 153.

¹² National Academy of Sciences, *op. cit.*

responsible for the bulk of the monetized damages. The 10 percent of plants with the highest damages generated 25 percent of the electricity but 43 percent of the monetized damages. The 50 percent of plants with the lowest damages per plant accounted for 25 percent of the electricity generation and 12 percent of the damages.

The largest single source of greenhouse gas (GHG) emissions in the United States is coal-fired electricity generating facilities. GHG emissions vary greatly from plant to plant, due to variations in heat rates. GHG variation is 0.95 to 1.5 tons per megawatt hour of electricity generated.

Electricity from Natural Gas

Natural gas facilities were evaluated using an approach similar to that for coal plants. The gas facilities evaluated included those owned by electric utilities, independent power producers, and combined heat and power facilities (co-generation) and each had a capacity of at least five megawatts. The aggregate damages from these 498 facilities amounted to approximately \$0.74 billion or \$0.16 per kilowatt-hour. Non-climate change damages associated with electricity generation from natural gas are an order of magnitude lower than damages from coal-fired electricity generation. A variation in damages per plant for natural gas plants was similar to that for coal plants: The 10 percent of plants with the highest aggregate damages accounted for 65 percent of the air-pollution damages produced by all 498 plants. The 50 percent of plants with lowest damages per plant accounted for only 4 percent of the aggregate damages. Damages per kilowatt-hour varied across natural gas plants just as for coal plants and ranged between \$0.15 per kilowatt-hour (95th percentile) down to \$0.005 per kilowatt-hour (5th percentile).

GHG emissions for natural gas plants were on average about half of the coal plants. The range of variation was between 0.3 tons per megawatt hour (5th percentile) and 1.1 tons per megawatt hour (95th percentile).

Electricity from Nuclear Power

The study relied on other studies to identify the externalities associated with nuclear generated electricity, noting that externalities are, in general, much lower than those for coal and natural gas. However, it was noted that perhaps the largest externality associated with nuclear power is the lack of closure of the fuel cycle and the resultant need to store both low- and high-level radioactive waste and fuel above ground. They do not mention, however, the possibility of public exposure to radionuclides that might be released in the event of a reactor accident.

Electricity from Wind

From a manufacturing and construction standpoint, externalities can be divided into “upstream” and “downstream” externalities. Upstream externalities relate to the mining, processing, fabrication, and transportation of raw materials and parts; because no fuel is used in the electricity generation process there are no air pollutants such as those for coal and natural gas. Downstream impacts have mainly to do with visual and noise impacts, impacts on avian species and bats, and land use effects that accompany the construction of any electricity generating plant together with transmission of the electricity to load centers. The study participants note that few life-cycle cost impacts for wind energy have been calculated, but that they are likely to be less than for coal and natural gas.

Electricity from Solar Energy

Like wind power, solar power emits no gaseous pollutants during operations to produce electricity. Upstream life-cycle activities are also similar to wind energy and include mining of materials for solar panels and the balance of system components used to convert the electricity to alternating current. Downstream life-cycle activities include electricity generation, storage, and disposal or recycling of worn-out panels which have the potential to generate large amounts of waste and improper disposal may lead to the possibility of leaching of toxic chemicals.

Electricity from Biomass

Biomass combustors have many of the same issues as fossil-fueled electricity generators. Emissions from the combustion of biomass can include polychlorinated biphenyl compounds; recent research has focused on enclosed systems. Non-climate change related damages from biomass generated electricity on a per kilowatt-hour basis might equal or even exceed those from coal in some cases.

1.3.5. Overall Assessment

Little work has been done to quantify, in the same terms, the external costs of various energy technologies. The National Academy of Sciences study is perhaps the most comprehensive available for United States energy production. It appears that European countries and ECU organizations have focused more effort towards the study and comparison of various energy technologies. One such study already cited did a more comprehensive analysis for European conditions. In contrast to the NAS study, the European effort did include an attempt at monetizing global warming effects. The monetized costs included those for global warming, public health, occupational health, and material damage. Selected results from this study are shown in Table 1.

Table 2. External Costs for EU Electricity Production (€/kWh), by Technology

Energy Technology	Euro Cents per kWh			
	Denmark	Britain	Germany	France
Coal and Lignite	3-6	4-7	5-8	7-10
Natural Gas	1-2	1-2	1	2-4
Nuclear	0.2	0.25	n/a	0.3
Biomass	3	1	0-0.8	1
Hydro	n/a	n/a	1	1
Photovoltaic	0.6	n/a	n/a	n/a
Wind	0.1	0.15	0.25	n/a

This enumeration of external costs does not include subsidies for each energy source. This should be included either as an addition to the market cost or should be separately identified as a social cost that should be included in a full evaluation of energy technologies. On external-cost grounds, both in the analysis of the National Academy of Sciences in the U.S. and the EU Commission, the overall assessment is that wind is the least costly energy technology.

1.4. Benefit-Cost Analysis: An Approach for Evaluating Cost-Effectiveness

To assess the costs and benefits of a Sandia wind farm, what's needed is an economic analysis approach that can (1) take into account market and non-market based costs and

benefits; and (2) capture them for the *agency* or owner of the renewable assets, the *non-agency* users of these renewable assets, and those *third parties* that are not users but are indirectly impacted by the assets. This report details an approach based on standard approaches for engineering economics and a benefit-cost classification scheme that can capture and effectively use these agency, non-agency, and third party designations.

1.5. Purpose and Scope of this Report

The purpose of this report is to describe an approach for estimating the costs and benefits associated with wind farm and other renewable energy projects, and to illustrate its use on a Sandia wind farm. Following an industry-standard benefit-cost approach based on life-cycle costing principles and a cost classification scheme, the analysis collects and then estimates the life-cycle benefits and cost of a wind farm of a particular size. The analysis includes initial uncertainty and sensitivity analysis to see how sensitive this economic result is to changes in many of the underlying parameters. Based on these preliminary results, the report suggests a path forward for further economic analysis. The analysis techniques used herein are applicable to the economic assessment of most if not all forms of renewable energy.

Section 2 describes the economic framework for classifying and estimating the costs and benefits of a wind farm. Section 3 then describes the analysis, including the initial cost and non-cost data, the sources for the particular parameters used, the results, and their implications. Section 4 summarizes and lists suggestions for further economic research.

2. A Framework for Estimating the Costs and Benefits of a Wind Farm

2.1. Life-Cycle Cost Analysis (LCCA)

Life-cycle cost analysis (LCCA) is the process of assessing the costs that occur over the intended life of a structure or set of assets. Often referred to as “cradle-to-grave” or “womb-to-tomb” analysis, its expressed purpose is to provide a formalized process for assessing these costs. It is used widely in many different disciplines and professions, including finance, social science, environmental science, project-appraisal, technology investment, and asset management.

Most LCCA frameworks follow a specific set of steps, conditions, and requirements to produce economic assessments of the most value to stakeholders. The analysis herein follows the detailed framework outlined in *ASTM Standards on Building Economics*,¹³ an industry-standard document that describes the necessary components and steps for not only life-cycle cost analysis, but also benefit-cost analysis, savings-to-investment ratios, net-benefit analysis, and uncertainty and sensitivity analysis. The economic approaches in this *Standards* document, for example, are used widely within the Department of Energy to estimate the economic costs, benefits, and other factors of building- and energy-related decisions.¹⁴

The essential components of this (or any other) LCCA framework include the following: first, an *agency* considers owning or using a particular set of assets that will perform some specific function over their intended *functional life*. For example, Sandia can consider installing a wind farm for Sandia’s use. Second, this agency explicitly or implicitly needs to compare the best of competing *alternate decisions*, most often composed of a *base case* (or “do nothing” strategy) or a new, alternate strategy. For example, Sandia’s do-nothing strategy would be to not install an on-site wind farm, and the alternate strategy would be to install one. Third, while based on engineering or other functional data these assets may operator for a very long time, there is an *analysis or study period* over which the agency is interested in accounting for costs. For example, a wind farm may last 100 years due to excellent design and meticulous maintenance, but for planning purposes Sandia may only want to consider costs and benefits over the next 20 years.

Next, costs that occur in different years of this analysis period need to be compared, specifically through their summation over the study period. Two primary factors change costs over the study period of an asset: (1) the changes in the prices of labor, capital, and materials to conduct operation, maintenance, and repair (OM&R) of the asset; and (2) the time value of money. To make them comparable, they need to be converted to equivalent values for a *base year*, which is typically the first year of the study period. The formula used to estimate life-cycle costs is

¹³ American Society of Testing and Materials, *ASTM Standards on Building Economics*, Fourth Edition, Philadelphia, PA, 2001.

¹⁴ For example, see the publications on the National Institute of Standards and Technology, Building and Fire Research Laboratory website (accessed at <http://www.nist.gov/publication-portal.cfm?defaultSearch=false&q=&authorlist=&researchfield=155&seriesName=&datefrom=&dateto=#> on December 5, 2010) for a list of the types of analysis to which this *Standards* document has been applied.

$$LCC = \sum_{t=0}^T \sum_{\{c_t\}} c_t \left(\frac{1+i}{1+r} \right)^t, \quad \text{Eq. 1}$$

where t is the particular year within the study period of T years, $\{c_t\}$ is the set of costs that occur in year t , i is the average *inflation rate* over the study period, and r is the average *nominal discount rate*, which includes the time value of money and inflation. Often with energy-related projects, different costs will have different inflation rates, e.g., for the increase in energy rates versus the increase in OM&R costs. Ultimately, when comparing the LCC of two alternate strategies or decisions, the one with the lowest LCC is the *cost-effective alternative*.

Finally, within this framework, benefits of a particular alternate are typically negative costs, i.e., they reduce the costs associated with a particular alternate.

2.2. Types of Costs and Benefits

While LCC analysis quantifies all costs and benefits associated with alternate strategies in dollar terms, thereby making direct comparison straightforward, there are useful groupings of costs and benefits that lend to analytical comprehensiveness and important economic insight. Following Ehlen (1997),¹⁵ costs can be grouped into three distinct, non-overlapping, and ultimately additive types:

1. *Agency* costs and benefits, which are the costs to the agency that own, maintains, and/or has economic decision authority over the set of assets. These are typically market-based. Example: costs and benefits to Sandia National Laboratories.
2. *Non-agency* costs and benefits, which are to entities that are not the direct owner(s) of the assets but use them directly. These are typically non-market based, or external in nature. Example: costs and benefits to Sandia engineers who have access to working wind farm.
3. *Third-party* costs and benefits, which to entities that are neither owners nor direct users of the assets. These are typically non-market based, or external in nature. Examples: costs and benefits to non-Sandians who benefit from reductions in carbon emissions, green-house gasses, and global climate change.

Agencies then have the ability to compare and weigh the relative merits of alternatives based on their effects on the agency, on those that use the alternatives, and all others.

2.3. Related Analyses

As illustrated by Figure 3, this LCCA approach and associated classification scheme provide a foundation for conducting benefit-cost analysis, net benefits analysis, savings-investment ratio analysis, and uncertainty and sensitivity analysis.

¹⁵ Ehlen, M.A., "Life-Cycle Costs of New Construction Materials," *Journal of Infrastructure Systems*, Vol. 3 No. 4, 1997.

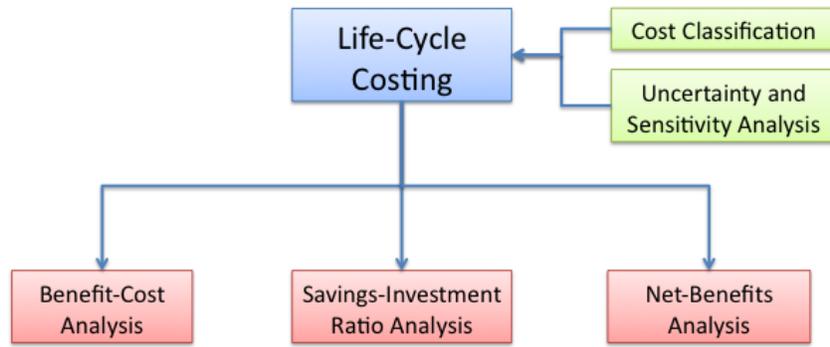


Figure 3. Structure of Economic Analysis Components

2.3.1. Benefit-Cost Analysis

Benefit-cost analysis uses the LCC framework and calculations to directly calculate and compare the costs and benefits associated with an alternate vis-à-vis the base case. The relative benefits of the alternative (its benefits minus any benefits of a do-nothing base case) are compiled using Eq. 1 and compared to the relative costs (its costs minus any costs of a do-nothing base case, also using Eq. 1), and used to compute the benefit-cost ratio

$$\text{Benefit - cost ratio} = \frac{B}{C} = \frac{\sum_{t=0}^T \sum_{\{b_t\}} b_t \left(\frac{1+i}{1+r} \right)^t}{\sum_{t=0}^T \sum_{\{c_t\}} c_t \left(\frac{1+i}{1+r} \right)^t}. \quad \text{Eq. 2}$$

If this B/C ratio is greater than one, the alternate is the cost-effective strategy.

2.3.2. Savings-Investment Ratio (SIR) Analysis

Savings-investment ratio analysis uses the LCC framework and calculations to estimate the savings associated with an alternative and compare them to the investment required to implement the alternate strategy. The savings of an alternative (its relative costs and benefits when compared with a base case, do-nothing strategy) are compared with the costs of investing in the alternate strategy, again using Eq. 1, and used to compute the savings-to-investment (SIR) ratio

$$\frac{S}{I}. \quad \text{Eq. 3}$$

If the S/I ratio is greater than one, the alternate is the cost-effective strategy.

2.3.3. Net Benefits Analysis

Net benefits analysis is another method based on LCCA fundamentals that gives analytical insight to the relative cost-effectiveness of alternate decisions or strategies. In this approach, the net benefits (the difference between the benefits) of an alternative vis-

à-vis the base case are computed. If greater than zero, the alternate is the cost-effective strategy.

2.3.4. Factor, Uncertainty, and Sensitivity Analysis

Three important follow-on analyses should be included in a life-cycle cost analysis: *factor analysis*, *uncertainty analysis*, and *sensitivity analysis*. Factor analysis provides important insight into which parts of the data and overall model are the largest contributing factors to overall life-cycle cost. For example, in a wind farm analysis, it's important to know whether the electricity costs, wind farm installation costs, or Renewable Energy Certificate (REC) costs are the largest factors driving life-cycle costs.

Second, with any analytical model or process there can be considerable uncertainty in the data, models, and associated parameters used to conduct the analysis. For example, in life-cycle costing and the above derivative calculations, there can be uncertainty in the appropriate study period, the expected life of the assets, the construction and OM&R costs, the inflation rate, and real discount rate. Furthermore, in the case of a wind farm, there is considerable uncertainty regarding the future electric power rates. This uncertainty can affect the analytical conclusion of whether or not implementing a Sandia wind farm is a cost-effective strategy. Qualitatively speaking, *uncertainty analysis* provides a means for assessing the effects of data uncertainty (i.e., whether the data are correct) on the analytical results, and *sensitivity analysis* provides a means for assessing the effects of model uncertainty (i.e., whether the model is correct) on the analytical results.

Uncertainty analysis is conducted after completion of the LCC-based cost analysis and associated benefit-cost or adjunct analysis. The “best-estimate” values of cost and associated LCC parameters were used and initial assessments of life-cycle cost-effectiveness were made. For uncertainty analysis, the analyst makes assessments of the uncertainty in these underlying parameters, and then re-calculates LCC and the associated measures using these variations in parameters. If these re-calculations indicate the particular strategy is still the cost-effective strategy, then the analyst can conclude that this strategy is “robust” or “insensitive” to potential variations in these data and parameters.

Finally, sensitivity analysis is used to determine if and how the calculations are sensitive to particular parameters or subsets of parameters. This sensitivity can be calculated, for example, by computing the changes in the LCC and other cost measures caused by, say, a 1 percent change in the data or parameter value. If the LCC and other computations are very sensitive to one or more of these parameters, then further more detailed analysis of this parameter and model may be warranted.

2.4. Analysis Process

Benefit-cost analysis and the supporting life-cycle cost calculations require a specific set of inputs, are conducted using specific set of steps, and generate specific results.

2.4.1. Inputs

To conduct life-cycle costing and related analyses, the analyst needs to provide the following information:

1. A statement of the **functional goal** and *performance requirements*¹⁶ of this goal, i.e., “provide electric power to community facilities in and around Sandia National Laboratories, i.e., the labs, Kirtland Air Force Base, and Albuquerque. The quantity of power should be 16 percent of current annual demand.”
2. A list of the **alternate strategies used to meet these goals**. These typically include (1) a base case or “do nothing” strategy, and (2) an alternate strategy, e.g., implementing a wind farm.
3. A **study period** over which the alternates will be evaluated, say 20 years.
4. “Best-guess” estimates of the costs associated with, where applicable, the construction, operation, maintenance, repair, and sometimes removal of the alternatives over the study period. These costs are typically provided in terms of what they would cost today to do, not in the year(s) in which they occur.
5. “Best-guess” estimates of the benefits associated with the, where applicable, activities that occur due to the alternate in question, over the study period. As with costs, these benefits are typically quantified in terms their value today, not their value in the year(s) in which they occur.
6. Who pays the costs and who receives the benefits, using the classification scheme in Section 2.2.

2.4.2. Analysis

Once prepared, the analyst uses these inputs to conduct the following analytical steps:

1. Use the “best-guess” costs and benefits of each alternative to compute the life-cycle cost of each alternative, where the set of costs (including benefits as negative costs) is computed using Eq. 1. The alternate with the lowest LCC is the cost-effective strategy.
2. Use the “best-guess” benefits of each alternate vis-à-vis the base case to estimate the total benefits, and use the “best guess” costs of each alternative vis-à-vis the base case to estimate the total costs, and then use Eq. 2 to compute the benefit-cost ratio of that alternate vis-à-vis the base case. The alternate with the highest B/C ratio greater than 1 is the cost-effective strategy among all alternatives (including the base case).

¹⁶ Performance requirements are the set of functional tasks that the asset or set of assets must meet. They are intended to be generic or abstract enough that alternate, competing strategies can be considered and compared. *Prescriptive requirements*, in contrast, are requirements that often prescribe specific techniques or technologies.

3. Conduct uncertainty and sensitivity analysis on the data, parameters, and models used. If this analysis does not change which alternate is cost-effective, then the results from Steps 1 and 2 hold. Otherwise, there are specific conditions for each alternate to be cost effective.

2.4.3. Outputs

A typical LCC and related analysis should produce at least the following:

1. A list of the performance goals;
2. A list of the costs and supporting parameters used in the analysis;
3. A list of the life-cycle costs associated with each alternate;
4. A list of the benefits, costs, and benefit-cost ratios of each alternate vis-à-vis the base case;
5. The qualitative or quantitative results of any and all uncertainty and sensitivity analysis conducted; and
6. A clear statement of which alternative is the life-cycle cost- and benefit-cost-effective alternative among the listed alternatives.¹⁷

¹⁷ Specifically, there may be another alternative that was not listed but that meets the performance requirements. Once identified as a potentially cost-effective alternative, it should be included in the analysis.

3. Benefit-Cost Analysis of a Sandia Wind Farm

Following the steps outlined in Section 2.4.2, we conducted an analysis of the potential costs and benefits of a Sandia wind farm as specified in Karlson (2009). While some of the steps herein appear superfluous or an over-complication of an otherwise straightforward economic analysis, they are provided as examples of how the approach can provide a simple but standard structure for conducting more comprehensive analysis that is of increased utility to Sandia energy and research stakeholders.

As noted above, there are many potential market and non-market costs and benefits associated with (1) providing electric power in general and (2) providing some of this power with renewable energy such as from wind turbines. These costs and benefits can be to agencies (e.g., Sandia National Laboratories and KAFB¹⁸), to non-agencies (direct users of the energy) and third parties (individuals who are indirectly affected by the electric power). This preliminary illustrative analysis focuses only on the market-based agency costs and benefits; future analysis should include these other types of costs and benefits.

3.1. Inputs

3.1.1. Performance Requirements

The performance requirements for our alternate strategies are relatively straightforward: to provide electric power (renewable or otherwise) to the Sandia National Laboratories facilities and to broader Kirtland Air Force Base, at an average level equal to 16 percent of annual demand. While not considered herein, additional performance requirements could include providing wind research facilities on site for Sandia energy scientists, engineers, and other researchers. These additional requirements would then provide the framework for accumulating costs and benefits associated with providing these wind facilities. For now, we do not include these in the analysis.

3.1.2. Alternate Strategies

Two alternate strategies were considered to meet this performance requirement of providing electric power to Sandia and KAFB:

- **Base case:** a “do nothing” strategy, where the current structure of power supply and usage is maintained, and
- **Alternative 1:** a Sandia wind farm strategy, where Sandia installs 15 wind turbines with a combined capacity of 30 MW. This farm would produce roughly 77 million kWh/yr of energy, or 16 percent of Sandia’s energy demand in the year 2008, based on modeled wind energy resource with a 29.3 percent capacity factor.

3.1.3. Types of Costs and Benefits

Standard Costs and Benefits

¹⁸ In the event that SNL and KAFB contract with an external company to own and operate the wind farm, SNL would still be the *agency* paying, say, a unit price for each kWh of renewable energy provided.

The standard cost associated with the alternatives considered include

- Costs of electric power,
- Costs of RECs (Renewable Energy Certificates) when no renewable power sources are used,
- Wind farm installation costs, and
- Wind farm operation, maintenance, and repair costs.

The benefits considered include

- Reduced energy costs, and
- Revenues from RECs.

3.1.4. Economic Assumptions

Table 3 lists the parameters and their best-estimate values (and sources) used to compute the costs and benefits associated with the two alternatives.

Table 3. Best-Estimate Parameter Values

Parameter (Unit of Measure)	Best Estimate	Source
2010 Energy Consumption (kWh/yr)	464,279,370	Karlson (2009) ¹⁹
Amount of Energy Generated by Wind Power	77,000,000	Karlson (2009)
Avg. Incr. in Electricity Consumption (%/yr)	1.00%	DOE EIA ²⁰
EPACT Required Renewable Energy (kWh/yr)	34,820,953	Karlson (2009)
Normal Electricity Cost (\$/MWh)	\$0.075	Karlson (2009)
REC Price (\$/MWh)	\$0.007	Karlson (2009)
Total Wind Farm “Overnight Cost” (\$)	\$57,690,000	Karlson (2009)
Annual Operation Maintenance Cost (\$/yr)	\$909,000	BK Karlson (2009)
Energy Price Inflation (%/yr)	1.90%	DOE EIA ²¹
Nominal Discount Rate (%/yr)	4.50%	OMB Circular A-94 ²²
Real Discount Rate (%/yr)	2.70%	OMB Circular A-94
Inflation Rate (%/yr)	1.80%	Computed from OMB Circular ²³

Two forms of inflation were used in the analysis: the change in prices of energy and the change in the average price of all goods. These two rates can differ significantly and

¹⁹ Karlson, *op. cit.*

²⁰ U.S. Department of Energy, U.S. Energy Information Administration, “Forecasts and Analysis of Energy Data,” accessed at <http://www.eia.gov/oiaf/forecasting.html> on December 5, 2010.

²¹ *Ibid.*

²² Office of the President of the United States, Office of Management and Budget, “Appendix C Revised December 2009 | The White House,” accessed at http://www.whitehouse.gov/omb/circulars_a094_a94_appx-c/ on December 6, 2010.

²³ The average annual inflation rate that is consistent with the OMB circular’s nominal and real discount rate can be computed as: inflation rate $i = [(1 + n) / (1 + r)] - 1$, where n = the nominal discount rate and r = the real discount rate.

since the primary costs herein are energy related, their change over time should be accurately measured.

3.2. Outputs

While there are a number of measures of cost-effectiveness listed in Section 2.3, we compute only two of them: life-cycle cost and benefit-cost ratio.

3.2.1. Life-Cycle Cost

Life-cycle costs were computed using an Excel spreadsheet and the values in Table 3. First, annual energy consumption at the base (Column #1 in the table) was estimated over our 30-year study period using the baseline 2010 consumption level of 460,000,000 kWh/yr and increasing it each year using the average annual increase estimated by the U.S Energy Information Administration.

Table 4. Life-Cycle Cost Calculations

Year	(1) Energy Consumption (kWh/yr)	(2) Base Case Grid Power Cost (\$2010)	(3) Base Case REC Cost (\$2010)	(4) Alternative Installation / OM&R Costs (\$2010)	(5) Alternative Grid Power Costs (\$2010)	(6) Alternative REC Revenues (\$2010)
1	464,279,370	34,820,953	243,747	57,690,000	29,249,600	519,993
2	468,922,164	35,169,162	246,184	909,000	29,597,810	519,993
3	473,611,385	35,520,854	248,646	909,000	29,949,501	519,993
4	478,347,499	35,876,062	251,132	909,000	30,304,710	519,993
5	483,130,974	36,234,823	253,644	909,000	30,663,471	519,993
6	487,962,284	36,597,171	256,180	909,000	31,025,819	519,993
7	492,841,907	36,963,143	258,742	909,000	31,391,791	519,993
8	497,770,326	37,332,774	261,329	909,000	31,761,422	519,993
9	502,748,029	37,706,102	263,943	909,000	32,134,750	519,993
10	507,775,509	38,083,163	266,582	909,000	32,511,811	519,993
11	512,853,264	38,463,995	269,248	909,000	32,892,642	519,993
12	517,981,797	38,848,635	271,940	909,000	33,277,282	519,993
13	523,161,615	39,237,121	274,660	909,000	33,665,769	519,993
14	528,393,231	39,629,492	277,406	909,000	34,058,140	519,993
15	533,677,164	40,025,787	280,181	909,000	34,454,435	519,993
16	539,013,935	40,426,045	282,982	909,000	34,854,693	519,993
17	544,404,075	40,830,306	285,812	909,000	35,258,953	519,993
18	549,848,115	41,238,609	288,670	909,000	35,667,256	519,993
19	555,346,596	41,650,995	291,557	909,000	36,079,642	519,993
20	560,900,062	42,067,505	294,473	909,000	36,496,152	519,993
21	566,509,063	42,488,180	297,417	909,000	36,916,827	519,993
22	572,174,154	42,913,062	300,391	909,000	37,341,709	519,993
23	577,895,895	43,342,192	303,395	909,000	37,770,840	519,993
24	583,674,854	43,775,614	306,429	909,000	38,204,262	519,993
25	589,511,603	44,213,370	309,494	909,000	38,642,018	519,993
26	595,406,719	44,655,504	312,589	909,000	39,084,151	519,993
27	601,360,786	45,102,059	315,714	909,000	39,530,707	519,993
28	607,374,394	45,553,080	318,872	909,000	39,981,727	519,993
29	613,448,138	46,008,610	322,060	909,000	40,437,258	519,993
30	619,582,619	46,468,696	325,281	909,000	40,897,344	519,993

The Base Case life-cycle costs were computed as the discounted present value of annual

$$\text{Grid energy costs} + \text{REC premiums.}$$

The Alternative 1 life-cycle costs were computed as the discounted present value of annual

$$\text{Wind farm installation cost} + \text{Wind farm OM\&R costs} + \text{Grid energy costs} - \text{REC revenues.}$$

The annual average cost of this electric power (Column #2) was computed using the 2010 cost of \$0.075 / kWh, and increased each year using the average annual increase in power costs forecast by DOE EIA.²⁴ The Base Case REC cost (Column #3) was estimated as a premium on 7 percent of the annual energy costs in Column 1.

To compute costs for the Alternative 1 Sandia wind farm, installation costs were estimated at \$57 million and annual OM&R costs at \$909,000,²⁵ both listed in Column 4. Next, Column 5 lists the power costs the base still pays with the wind farm, which is 84 percent of power in the 2010. Finally, with a wind farm, Sandia receives REC revenues based on the 75 MWh/yr of power it generates across the study period.²⁶

To compute present values of the annual costs, the costs in each year were computed to current-year values using either the energy inflation rate or the general inflation rate: energy costs (Columns 1, 2, 3, 4, 5) were inflated using the energy inflation rate in Table 3; wind farm installation and OM&R costs were inflated using the general inflation rate. The nominal interest rate was then used to compute the present value of these future, inflated costs.

The life-cycle costs of each alternative are then the sum of the present value of each cost. Table 5 lists their values, rounded to the nearest 10 million. The wind farm, with a life-cycle cost of \$790 million, is the cost-effective alternative between our two alternatives.

Table 5. Life-Cycle Cost, by Alternative

Alternative	Life-Cycle Cost
Base Case (no Wind Farm)	\$850,000,000
Alternative 1 – Wind Farm	\$790,000,000

To give more detail on these values, Figure 4 compares the annual costs of each alternative. The present value of Base Case annual costs declines over the study period due to the effects of the nominal discount rate (4.5%) being greater than the annual increases in energy prices (1.9%). The Alternative wind farm starts out with greater costs (due to installation), but the energy savings and REC revenues (and decline in REC payments) creates lower annual costs than the Base Case over the rest of the study period.

²⁴ *Ibid.*

²⁵ Karlson, *op. cit.*

²⁶ After completion of this analysis, it was determined that the REC revenues would be twice this amount, since KAFB is on federal land. Our result of the wind farm being the cost-effective alternative does not change due to this REC revenue doubling, in fact, it strengthens the cost effectiveness.

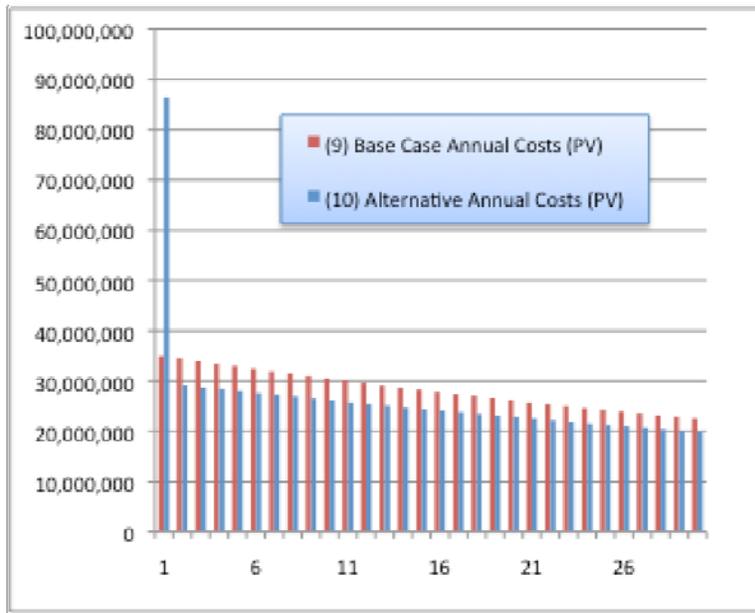


Figure 4. Annual Present-Value Cost, by Alternative

Next, Figure 5 displays the cumulative present value costs, by alternative, over the study period, where the values at the right-most ends of each line, in Year 30, are the life-cycle cost of each alternative.

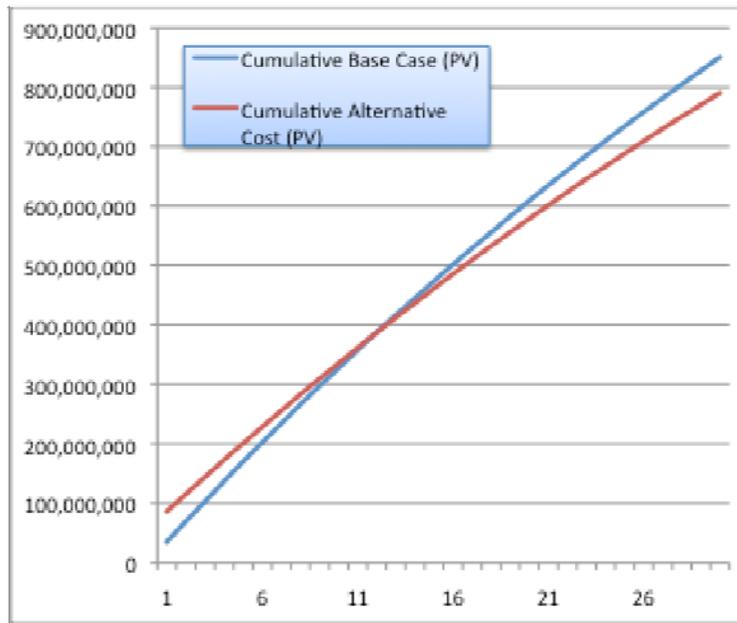


Figure 5. Cumulative Present-Value Cost, by Alternative

As indicated by this second figure, the Base Case has a lower cumulative present value in the early years of the study period, but at Year 12 the Alternative 1 wind farm has a lower cumulative present value and thus becomes the cost-effective alternative. Said differently, the wind farm investment breaks even after 12 years.

3.2.2. Benefit-Cost Ratio

Given the two alternatives, we computed a benefit-cost (B-C) ratio for the alternative wind farm vis-à-vis the base case “do nothing” strategy. Benefits are computed as the sum of reduced energy costs (lower power use plus no REC premium) and the REC receipts. The costs of the alternative are the sum of installation costs and annual OM&R costs. Table 6 lists the individual values, the sums of costs and benefits, and the resulting benefit-cost ratio of 2.3. Given that the benefit cost ratio is greater than 1, the wind farm is the cost-effective alternative.

Table 6. Benefit-Cost Ratio Calculations: Alternative 1 Wind Farm

Benefits	\$191,000,000
Reduced Energy Costs	\$178,000,000
REC payment	\$13,000,000
Costs	\$84,000,000
Installation	\$58,000,000
O&M	\$26,000,000
Benefit-Cost Ratio	2.3

3.2.3. Uncertainty and Sensitivity Analysis

To assess whether the cost-effectiveness of the alternatives are sensitive to uncertainties in the underlying parameters, we conducted uncertainty analysis on the set of parameters listed in Table 7. For each parameter, the LCC and B-C values were recomputed for the two lower and upper values listed in the “Uncertainty Range” column. These result in changes in the upper and lower values of the Base Case and Alternative LCC and the B-C ratio.

Table 7. Uncertainty Analysis Parameter Values and Results

Parameter (Unit of Measure)	Best Guess Value	Range of Uncertainty	Range of Base Case LCC (\$M)	Range of Alt 1 LCC (\$M)
Baseline values	-	-	\$850 M	\$790 M
Normal Electricity Cost (\$/kWh)	\$0.075	[\$0.03, \$0.10]	[\$343, \$1,132]	[\$355, \$1,032]
Increase in Elec. Cons. (%/yr)	1.90%	[0.5%, 4.0%]	[\$796, \$1,298]	[\$737, \$1,235]
Energy Inflation Rate (%/yr)	1.00%	[0.5%, 2.0%]	[\$712, \$861]	[\$673, \$800]
Average REC Price (\$/MWh)	\$0.007	[\$0.0, \$0.02]	[\$844, \$861]	[\$790, \$790]
Total Wind Farm Cost (\$ M)	\$58.0	[\$30M, \$80M]	[\$850, \$850]	[\$760, \$813]
Annual OM&R Cost (\$ K/yr)	\$910	[\$500, \$1,500]	[\$850, \$850]	[\$782, \$802]
Nominal Discount Rate (%/yr)	4.5%	[1.0, 6.0]	[\$1,400, \$708]	[\$1,258, \$670]

While it is not obvious from this table’s values, the ranges of computed LCCs do indicate often significant changes in the life-cycle costs of the alternatives, but only one of which causes the Alternative 1 wind farm to not be cost-effective: significant decreases in traditional electric power rates. Specifically, if rates today were an estimated \$0.04 per kWh instead of the best-estimate value of \$0.075 per kWh, the Base Case “do nothing” strategy is life-cycle cost-effective. The other parameters in the table also cause changes in life-cycle costs at a significantly lower level of effect, and none of the others cause the Alternative 1 wind farm to no longer be cost-effective.

This effect of rates is further illustrated by our sensitivity analysis of our LCC model for the Base Case and Alternative 1 strategies. For each of the parameters listed in Table 8, we increased its value by 10 percent and then computed the percent increase in life-cycle costs of each alternative. As shown in the table (and Figure 6), increases in 2010 base-year electricity costs has the greatest effects on LCC, in fact almost a one-to-one correlation.

Table 8. Sensitivity Analysis: Effects on LCC of 10% Increase in Parameter Value

Parameter	BC % Change	Alt 1 % Change
Normal Electricity Cost (\$/kWh)	9.9%	9.2%
REC Price (\$/MWh)	0.1%	0.0%
Total Wind Farm Overnight Cost (\$)	0.0%	0.7%
Annual Operation Maintenance Cost (\$/yr)	0.0%	0.2%
Energy Inflation (%/yr)	2.5%	2.3%
Avg. Annual Increase in Electricity Consumption (%/yr)	1.3%	1.4%

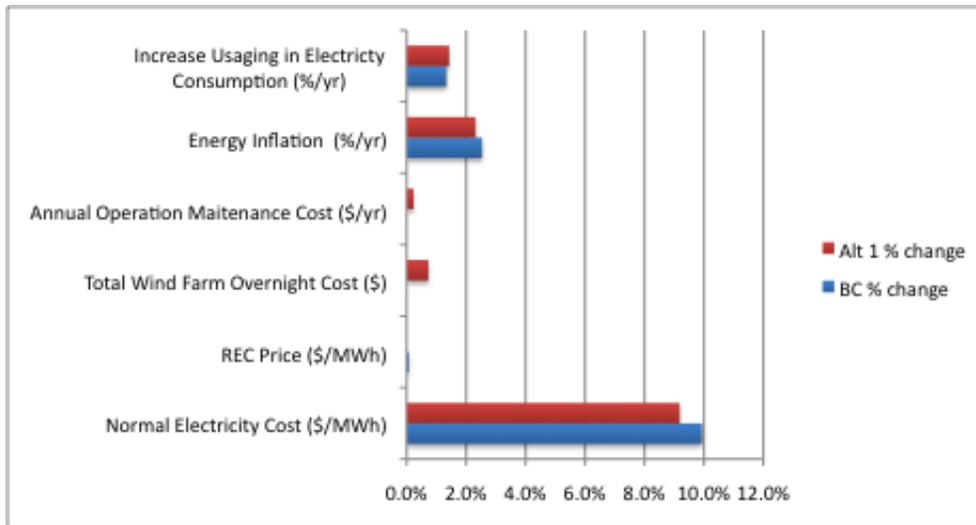


Figure 6. Effects on LCC of 10% Increase in Parameter Value

The next largest effect is the increase in energy inflation, where a 10-percent increase increases LCC by 2.3 – 2.5 percent. Note, however, that it increases the Base Case “do nothing” LCC more than the Alternative 1 wind farm LCC. That is, the more the rate increases, the more cost-effective the wind farm becomes.

The next significant effect is the annual average increase in energy consumption, which increases the Alternative 1 wind farm LCC more than the Base Case LCC, albeit a small amount. This is due to the fact that over time, the wind farm generates a smaller fraction of overall power consumption,

3.3. Discussion

Given the data used in this preliminary analysis, our LCC calculations suggest that the installation of 30 MW of wind generation capacity at Sandia National Laboratories would be a cost-effective decision, even just on market-based cost grounds. By providing its own source of on-site, low-cost power, SNL lowers its effective rate of power: comparing

Columns 2 and 5 in Table 4, the wind farm reduces annual energy costs by an estimated \$5 million per year (in 2010 values), by swapping out (expensive) grid power and swapping in (much less expensive) renewable energy.

This effect of reduced grid consumption is reinforced by the sensitivity analysis that shows that the largest two factors that influence LCC are the 2010 normal electricity costs followed by energy inflation. By lowering the effective rate of power, the wind farm alternative has the largest downward effect on the life-cycle costs of providing electric power to Sandia National Laboratories.

Upon overall inspection of this preliminary analysis, one glaring omission in our uncertainty analysis is the uncertainty regarding how much electric power a Sandia wind farm would generate. If the Alternative 1 wind farm generates significantly less than the “best-estimate” value of 75 MWH/yr, a wind farm may no longer be life-cycle cost-effective. Further work should be conducted to determine the uncertainty in this wind farm output and the effect of its change in parameter value on the overall LCC calculations.

4. Summary and Suggestions for Future Work

4.1. Summary

This report describes a preliminary economic analysis of the cost-effectiveness of installing a wind farm at Sandia National Laboratories and Kirtland Air Force Base. Using data from previous studies, government data sources, and other cost analyses, the analysis estimates the life-cycle costs and benefit-cost ratio associated with two alternative power strategies for Sandia: (1) a base case “do nothing” strategy, where the current power supply is maintained for the next 30 years; and (2) a Sandia wind farm strategy that provides an estimated 16 percent of 2008 Laboratory demand for electric power.

Following a standard life-cycle costing framework and set of cost calculations, agency costs (costs to Sandia National Laboratories) were computed over the 30-year study period. For the base case “do-nothing strategy,” life-cycle cost is based on grid-power costs and REC premiums. For the Alternative 1 wind farm strategy, life-cycle cost is based on wind farm installation costs, wind farm annual OM&R costs, reduced grid-power and REC costs, and REC receipts (which are a benefit, or negative cost). Life-cycle costs for the two alternatives were \$850 million and \$790 million in present value terms, respectively, suggesting that the wind farm is the cost-effective strategy.

Uncertainty and sensitivity analysis indicate that grid-power consumption levels and energy prices have the largest effect on life-cycle costs. By using renewable energy that costs less over the study period than grid power costs, a wind farm puts significant downward pressure on power costs for SNL. Other factors that influence LCC are the increases in energy consumption over time and the increase in energy prices over time (i.e., energy inflation), but both have significantly lower influence on LCC. Finally, the cost-effectiveness of the wind farm appears to be insensitive to significant changes in the nominal discount rate, real discount rate, or rate of price inflation.

Inspection of the Figure 5 indicates that a wind farm is initially more expensive in LCC terms than a “do-nothing” strategy, but the farm pays for itself in an estimated 12 years. This payback time period appears to be insensitive to changes in many of the underlying parameters, except for major changes in the level of 2010 energy prices.

4.2. Suggestions for Future Work

Given the preliminary nature of this analysis, however, specific strong conclusions about the cost-effectiveness of wind technologies at Sandia should not be made until further, more detailed analysis is conducted. This further analysis should include the following:

1. **Better data on current and future supply and demand of electric power at KAFB.** The largest factor affecting the level and potential changes in life-cycle costs is the level and price of electric power provided and used at KAFB/SNL. Significant errors in either of these parameters could significantly change the LCC values computed for each alternative.
2. **Better data on the potential wind power that can be supplied by a Sandia wind farm.** A significant factor influencing the cost-effectiveness of a wind farm

is the value of potential annual energy that can be generated by the wind farm. The current estimate is based on mesoscale models; new estimates could significantly change life-cycle costs. Observed on-site wind resource data should be used when available and is part of the ongoing feasibility study at Sandia.

3. **Better data on the current and future rate structure of RECs.** This study uses relatively basic assumptions about how RECs are applied to SNL power operations, and how SNL would benefit from REC revenues if it had onsite renewable energy.
4. **Better information on how others have implemented wind farms.** The analysis herein makes the basic assumption that Sandia would pay for the installation and maintenance of the wind farm. Other means of implementation, such as contracting with a third party for the wind farm and simply paying this third party a fixed rate for wind power, may have inherent costs and benefits that are important to the overall decision.
5. **Inclusion of non-traditional, non-agency and third-party costs.** While the preliminary analysis indicates cost-effectiveness for renewable technologies at SNL, further inclusion of other costs would better investigate and illustrate the inherent costs and benefits to the surrounding Albuquerque communities, the State of New Mexico, the Departments of Energy and Defense, and the broader global climate.

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