A Chicago Case-Study of Frontier Technologies in Local Power Generation:

Offshore Wind, Rooftop Solar Panel and, Solid Oxide Fuel Cells

Alex Boghosian, Patrick Lin, Ruinan Liu, Zsolt Terdik
December 8, 2010

1 Background

Coal provides 26% of global primary energy needs and generates 41% of the world's electricity. Coal generated 49% of US' electricity in 2007[1]. However, the production and use of coal has negative environmental impacts on the use of land and water as well as air quality and greenhouse gas emissions. Additionally, the use of coal raises public health and safety concerns. In response to these concerns, a variety of alternative power generation methods have been developed. In addition to reducing the negative environmental and health impacts, these alternative technologies represent a diverse mix of energy sources. This diversity improves the robustness of the US energy supply.

In this paper, we will discuss local methods of energy generation and their applicability to Chicago. Focusing our analysis on a specific city provides a real world context in which to address questions of local energy prices, availability of natural resources such as sunlight and wind, and financial and tax incentives. This analysis can be used more generally as a case study for the feasibility of local power generation in other large metropolitan centers.

There are two coal plants currently operating in the City of Chicago. Fisk 19 has been operational since 1959. Due to its age, by modern standards, the production methods are inefficient and environmental harmful. However, the low price of coal-generated electricity prohibits cleaner technologies, especially the less competitive frontier technologies. Frontier technologies have lower environmental impacts, but suffer from high capital and operating costs. However, if enough attention is paid to the R&D and implementation of the technologies, it is possible that cost of frontier technologies may be reduced to the point where they are cost competitive with coal.

In this study, we chose an energy portfolio containing three frontier technologies: offshore wind, photovoltaic, and solid oxide fuel cells. This combination is environmentally friendly and generates a smooth supply of electricity. The wind and solar technologies have low environmental impacts, while the solid oxide fuel cells smooth the energy fluctuations inherent to wind and solar. For each technology a consistent levelized cost of energy is carried and high-, base-, and low-cost scenarios are considered.

1.1 Coal

The environmental impacts of coal-based electricity can be seen at every stage of processing. Land disturbance and water pollution are two negative environmental impacts of coal mining. In addition, there are nitrogen oxide and particulate emissions generated during transportation. Coal plant emissions also degrade the local air quality. Processing coal emits carbon dioxide, sulfur dioxide, nitrogen oxide and mercury. Since the Clean Air Act curtailed the

---

[1] "Coal Facts 2009." *World Coal Association*. The World Coal Institute, 01 Oct 2009. Web. 8 Dec 2010. <http://www.worldcoal.org/resources/coal-statistics/>

sulfur dioxide and nitrogen oxide emissions, the largest environmental impact of coal plant emissions is the threat of global warming.[2]

Many of the environmental implications of burning coal have analogs in the way coal impacts human health. Mining coal results in 342 deaths/TerraWatt-Year[3], and there are significant health risks associated with gas emissions for communities living near coal plants. A study done in 2002 showed that communities near the older coal plants in Chicago had higher rates of asthma and increased mortality[4] [5].

Exacerbating these environmental and health threats is the grandfather clause of the Clean Air Act. The grandfather clause stated that all new coal plants have to be built with respect to the cleanest technologies available while older coal plants need not adhere to the same standards because they will soon be retired. This policy resulted in coal plants operating below emission standards for longer than initially expected. A study showed that removing grandfathering from Clean Air Act regulations in 1985 would have resulted in a 60% reduction in emissions by 1995 [6].

Fisk 19 is one of two coal plants operated by Midwest Generation in the city of Chicago. It is a grandfathered, subcritical coal plant burning subbituminous coal, which has the highest sulfur and carbon content[7]. Fisk is located in Pilsen, a neighborhood of Chicago with a population of 44,031[8].

Fisk 19 has been operational since 1959. Like most coal plants in the United States, Fisk operates a pulverized fuel boiler (PF)[9], which burns finely ground coal to drive a steam turbine coupled to an electric generator to produce electricity. PF boilers can be classified according to the temperature at which they generate steam. Subcritical boilers generate steam at pressures below 221.2 bar, and super critical boilers generate steam at pressure above 221.2 bar. Supercritical PF boilers are more efficient than subcritical PF boilers, and also have lower emissions[10]. Subcritical PF units have generating efficiencies of 33-37%, where the generating efficiency is defined to be the fraction of the thermal energy in the fuel that is accounted for in the net electricity produced.

---

[2] Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[3] Berry, Stephan. "Conventional Energy Sources." Energy and Energy Policy. University of Chicago. Chicago. 06 Oct 2010. Lecture

[4] "Summary of Results from Harvard School of Public Health Illinois Power Plant Study." (2008): Web. 8 Dec 2010.

[5] Jonathan I. Levy, *et al*, "Using CALPUFF to evaluate the impacts of power plant emissions in Illinois: model sensitivity and implications." Atmospheric Environment, Volume 36, Issue 6, February 2002, Pages 1063-1075.

[6] Garth Heutel,. "Plant vintages, grandfathering, and environmental policy", Journal of Environmental Economics and Management, In Press, Corrected Proof, Available online 8 August 2010

[7] "Annual Electric Generator Report." 31 12 2008. n. pag. *EIA-860*. Web. 8 Dec 2010. <http://www.eia.doe.gov/cneaf/electricity/page/eia860.html>.

[8] http://en.wikipedia.org/wiki/Lower_West_Side,_Chicago

[9] "Annual Electric Generator Report." 31 12 2008. n. pag. *EIA-860*. Web. 8 Dec 2010. <http://www.eia.doe.gov/cneaf/electricity/page/eia860.html>

[10] Ansolabehere, S., and J Beer. "The Future of Coal: An Interdisciplinary MIT Study." *Massachusetts Institute of Technology* (2007): n. pag. Web. 8 Dec 2010

According to Midwest Generation's 2003 Fact Sheet[11], Fisk 19 outputs 326 MW and generated enough power to meet the electricity demands of 381,000 households, which is 33% of the 1.15 million households reported by the 2000 census[12]. The same publication claims that nitrogen oxide and sulfur dioxide emissions are "well below current state and federal EPA limits." Nitrogen oxide reduction technology, installed in 2002, reduced nitrogen oxide emissions by 50%[13]. Fisk also installed sulfur dioxide scrubbers, which reduced SO2 emissions below the cap and trade limit set by the Clean Air Act.[14] However, a 2002 study showed that Fisk is the cause of 1,000 asthma attacks per year, 200 emergency room visits per year, and 15 deaths per year.[15]

The negative effects of coal emissions have lead the industry to work towards decreasing emissions. Carbon sequestration, scrubbers, and coal gasification are some examples of technologies that aim to mitigate the negative effects of coal-based power. For Fisk 19, a subcritical plant, installing carbon dioxide amine scrubbers will decrease efficiency from 35% to 25%, resulting in a high cost of electricity[16].

We adopt an LCOE model assuming a capacity factor of 85%. The capacity factor is defined as the amount power a plant outputs for a given unit of time divided by power output if the plant were to operate at nameplate capacity for the same amount of time. A capacity factor of 85% is standard for PF plants[17]. As Fisk is a subcritical plant, we may assume that Fisk operates at 35% efficiency. We also assume there are no carbon dioxide costs, and take the total capital costs to be 1,575$\kwh[18].

1.2 Offshore Wind

Like all other renewable energies, offshore wind power offers diversity for America's energy portfolio. It has no carbon emissions, which contributes to the amelioration of global warming. Globally there are 54,813 MW of offshore wind projects under review or construction while 2,377 MW are operational.

Offshore wind possesses great advantages over land-based wind. Offshore winds tend to blow harder and more uniformly than on land, allowing for increased electricity generation and smoother, steadier operation[19]. Areas with potential offshore wind resources in the U.S. frequently correspond with the more populous coastlines. This means that by adopting offshore wind power, costs incurred by long-distance transmission will be avoided. There are abundant offshore wind

---

[11] "Fisk Generating Station." *Edison International*. Midwest Generation, 01 Jan. 2005. Web. 8 Dec 2010. <http://www.edison.com/ourcompany/emg.asp?id=1580

[12] http://quickfacts.census.gov/qfd/states/17/1714000.html

[13] "Fisk Generating Station."

[14] Kim, Amy Hee, Jon Handy, and Kendrick Sands. "Future of Coal in Illinois: Case study Fisk 19." *Big Problems Curriculum in the College*., 2008. Web. 8 Dec 2010.

[15] "Summary of Results from Harvard School of Public Health Illinois Power Plant Study."

[16] "Future of Coal in Illinois: Case study Fisk 19."

[17] Woods, MC, and PJ Capicotto. "Cost and Performance Baseline for Fossil Energy Plants. Volume 1: Bituminous Coal and Natural Gas to Electricity Final Report." (2007): Web. 8 Dec 2010.

[18] http://www.netl.doe.gov/energy-analyses/refshelf/

[19] "Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers", National Renewable Energy Laboratory, September, 2010

resources in the U.S.: the gross resource quantified by state, water depth, and distance from shore and wind class throughout a band extending out to 50 nautical miles from U.S. coastline is estimated at more than 4,000 GW, roughly four times the generating capacity currently carried on U.S. electric grid[20].

In 2008, the U.S. Department of Energy (DOE) published a report that examines the technical feasibility of using wind energy to generate 20% of the nation's electricity demand by 2030. The 20% Wind Scenario requires U.S. wind power capacity to grow from 11.6 GW in 2006 to more than 300 GW over the next 23 years, of which 50 GW is to be generated by offshore wind. The state of Illinois has the Renewable Energy Portfolio of 25% by year 2025. To hit these targets, offshore wind is an indispensable component.

Current offshore wind development remains in shallow water areas (0-15m), however, deepwater areas have higher amounts of resources and cast the least impact on human lives. Furthermore, the majority of US offshore wind resources reside in deepwater. Thus the frontier technology of offshore wind goes hand in hand with deepwater objective. To analyze the technology status and its frontier part/trend, technologies are composed by three major components: turbines, operation & management and substructure.

The size of the turbine is a critical part of the Wind Turbine Generation System. Utility-scale onshore turbines have sizes between 900kW to 2MW per turbine[21]. Compared to land-based turbines, transportation and size limits are less constrained offshore and the noise requirement is low, so that the optimum turbine size can be greater than onshore ones. The current offshore turbines range from 2MW to 5 MW. There is no physical limit that prevents building 10-MW or larger turbines and several advanced producers around the world have been experimenting[22]. However, physical scaling laws do not allow some components to be increased in size without a change in fundamental technologies. Some of these technologies include a variety of stiffer, lightweight composite materials and new composite manufacturing methods, lightweight, high-speed rotors, direct-drive generators and large gearbox technologies that can tolerate slower rotational speeds and larger scales[23].

The operation and maintenance of offshore wind farms is more difficult than land-based ones. Hence the reliability of the WGTs and their accessibility are is an important area of ongoing development. New turbine designs must place a higher premium on reliable designs and low-cost in situ repair methods. Likewise, new materials must be selected for their durability and environmental tolerance. Emphasis should be placed on avoiding large maintenance events that

---

[20] "Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers", National Renewable Energy Laboratory, September, 2010

[21] McCaffrey B. (2005) Wind Turbine Technology Overview. Global Energy Concepts.

[22] Vidal, John. "Engineers Race to Design World's Biggest Offshore Wind Turbines | Environment | The Guardian." *Latest News, Comment and Reviews from the Guardian | Guardian.co.uk*. The Guardian, 26 June 2010. Web. 5 Dec. 2010. <http://www.guardian.co.uk/environment/2010/jul/26/offshore-turbine-britain>.

[23] Musial W., Ram B. (2010) Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers. National Renewable Energy Laboratory

require deploying expensive and specialized equipment[24]. The trend for O&M is to implement personnel access platforms to facilitate maintenance and provide emergency shelter, to equip operators remotely with intelligent turbine-condition monitoring and self-diagnostic systems to manage O&M, predict weather windows, minimize downtime and reduce the equipment needed for up-tower repairs[25].

The current design philosophy for wind farms in water depths up to 20 ~ 30 m is based on the monopole: a large steel tube with a wall thickness of up to 60 mm and diameters of up to 6 m. Piled foundations have long been adopted around the world for supporting offshore oil and gas platforms. There exist well-established recommended practices and guidelines for the design of piles and grouted connections[26]. Tripods, jackets, and trusses are proposed for transitional water (30-50m), which uses fixed-bottom jacket (lattice) or multi-pile substructures to provide stiffer base for turbines. New vessels for deeper deployments may be needed. Floating Structure is proposed for deep-Water case (50-100m). Floating substructures decouple from the bottom and allow site independence, which may allow a greater degree of mass production and less work at sea. Typical substructures under consideration include semi-submersibles, spar buoys, and tension-leg platforms.[27].

1.3 Rooftop Thin Film Solar Panels

Current research in photovoltaic (PV) panels addresses two complementary limitations: efficiency and price[28]. Much of the work in higher efficiency solar cells is a result of the incorporation of solar concentrators that focus the light onto the panel in order to increase the efficiencies. These methods can yield panels with conversion efficiencies up to to 41.6%[29], however the solar concentrators do not operate efficiently under diffuse lighting.[30] Given the diffuse light conditions in Chicago, we chose to focus on frontier technologies in low-cost PV.

The first generation solar panels, and still the most popular PV technology, utilize crystalline silicon wafers to generate electricity from sunlight. Wafers are most often composed of either monocrystalline or polycrystalline silicon, which also serves as the most significant cost to wafer based cells, accounting for 50% of the cost of every cell based on raw silicon alone[31]. The

---

[24] Musial W., Ram B. (2010) Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers. National Renewable Energy Laboratory

[25] Offshore Design Engineering (ODE) Limited. (2007) Study of the Costs of Offshore Wind Generation: A Report to the Renewables Advisory Board & DTI.

[26] Garrad Hassan & Partners, Tractebel Energy Engineering, et al. (2001) Offshore Wind Energy Ready to Power a Sustainable Europe.

[27] Musial W., Ram B. (2010) Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers. National Renewable Energy Laboratory

[28] Rohatgi, A., A. Ristow, and V. Yelundur. "Cost and Technology Roadmaps for Cost-Effective Silicon Photovoltaics." (2003).

[29] Cheyney, Tom. "NREL Confirms Spectrolab Solar Cell Hits New Conversion Efficiency Record of 41.6% - Photovoltaics International." Photovoltaics International. 27 Aug. 2009. Web. 28 Nov. 2010. <http://www.pv-tech.org/news/_a/nrel_confirms_spectrolab_solar_cell_hits_new_conversion_efficiency_record_o/>.

[30] "NREL: Dynamic Maps, GIS Data, and Analysis Tools - Solar Maps." National Renewable Energy Laboratory (NREL) Home Page. Web. 28 Nov. 2010. <http://www.nrel.gov/gis/solar.html>.

[31] Derbyshire, Katherine. "Wafer-based Solar Cells Aren't Done Yet | Renewable Energy News Article." Renewable Energy World - Renewable Energy News, Jobs, Events, Companies, and More. 9 Jan. 2009. Web. 02

price dependency of solar cells on silicon became especially evident in 2006 when there was a worldwide shortage in the high-grade crystalline silicon that was needed for wafer production to the point where previously uneconomical options such as processing lower grade metallurgical grade silicon were seriously considered[32].

As a result, researchers began looking at ways to reduce the amount of silicon needed in the production of solar cells. Thin-film technology became a promising option to reduce the raw material costs associated with crystalline silicon. Further cost reductions can be achieved by using amorphous silicon that reduces the costs associated with crystallization. However, amorphous silicon cells are subject to degradation between 15-35% when exposed to the sun. In order to overcome this degradation and improve performance, novel composite structures of multiple thin films are used.

One solution to this problem is to stack multiple layers of thin film on top of each other improving total light absorption. This arrangement improves performance in diffuse and cloudy light conditions as the multiple layers capture a wider range of the spectrum than crystalline panels in similar conditions. In the end however, energy conversion efficiencies of 5-8% are lower than the efficiency rates, 11-16%, of crystalline panels. Furthermore, the complexity of the manufacturing process may limit yield and drive up manufacturing costs outweighing any raw material price reductions[33].

Reducing costs extends beyond the solar panel itself. The cost of the panel typically only makes up half of the initial costs in a solar system installation. Inverters, installation, and structural (framing, cabling etc.) costs all play significant roles in determining the upfront cost. Furthermore, there are also maintenance costs that need to be considered throughout the life of the project. Thin-film laminates do not require framing and hence reduce structural costs. The panels are unrolled and directly applied to existing roofs with an adhesive. This installation method also cuts down on the weight of the solar system, which may in turn further reduce structural costs. The lightweight and durable nature of thin-films has created a new category of building integrated photovoltaics (BIPV). The easy installation and unobtrusive nature of BIPV makes them ideally suited for urban environments.

There does not appear to be large cost reductions on the horizon for inverters, which are necessary to convert DC current from the panels to grid compatible AC current. The learning curve for inverters, which indicates price and performance improvements, stands at 10% compared to 20%, which is the industry value for PV panels. This means that improvements in inverter technology will not keep pace with PV panel improvements. Furthermore, inverters are the driving force behind system maintenance costs. Manufacturers feel that an inverter beyond a lifespan of 15 years is not a realistic target to achieve[34]. Hence, cost of the complete solar system

---

Dec. 2010.
<http://www.renewableenergyworld.com/rea/news/article/2009/01/wafer-based-solar-cells-arent-done-yet-54443>.

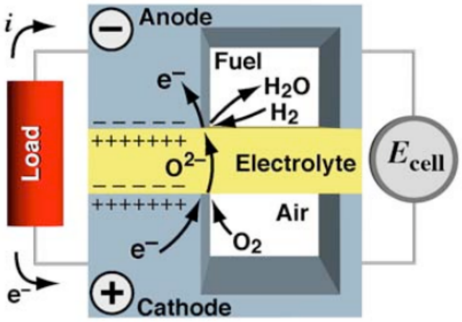
[32] Kho, Jennifer. "Solar: Doing the Dirty." RedHerring.com ~ The Business of Technology. 8 Dec. 2006. Web. 02 Dec. 2010. <http://www.redherring.com/Home/20157>.

[33] "Solar Cell Technologies." Solarbuzz | Solar Energy Industry Research and Consultancy. Web. 03 Dec. 2010. <http://www.solarbuzz.com/Technologies.htm>.

[34] Margolis, R. "A Review of Pv Inverter Technology Cost and Performance Projections." National Renewable

will depend on advances in other fields such as panel and structural cost reductions, not inverter cost reductions.

1.4 Solid Oxide Fuel Cells/Bloom Box



Cathode charge transfer:

$$O_2(g) + 4e^-(c) \rightleftharpoons 2O^{2-}(el)$$

Anode charge transfer:

$$H_2(g) + O^{2-}(el) \rightleftharpoons H_2O(g) + 2e^-(a)$$

Net:

$$H_2(g) + \frac{1}{2}O_2(g) \rightleftharpoons H_2O(g)$$

An additional technology that we chose to investigate was solid oxide fuel cells (SOFC). In contrast to both solar and wind systems, fuel cells promise a locally generated base load energy supply. The underlying science is based on an electro-chemical conversion of natural gas (or bio-mass) to electricity. Natural gas flows into the anode where it is reformed to hydrogen molecules (H_2) and residual carbon. Meanwhile, oxygen molecules are reduced to form oxygen ions at the cathode. The middle layer, a solid ceramic electrolyte, allows the diffusion of oxygen ions from the cathode to the anode, while prohibiting the migration of electrons. Finally, at the anode, the oxygen ions combine with the hydrogen gas and the residual carbon to form water, carbon dioxide, and electrons. The electrons flow from the anode back to the cathode across a circuit, doing work in the process. Once the electrons return to the anode, they reduce oxygen gas and the process repeats[35]. The simplified oxidation-reduction reactions are shown above[36]

The preceding explanation is the common basis for all solid oxide fuel cells. Within this general framework there are several material and design challenges that need to be addressed in order to create marketable fuel cells. First, the permeability of the electrolyte to oxygen ions is temperature dependent (Stamboulli). In order to sustain the diffusion of oxygen ions, operating temperatures must range from 700-1000 C. At these operating temperatures, thermal stress has different effects on the various materials within the system, leading to cracking and performance degradation. One active area of research is finding different materials for the electrolyte that allow for lower operating temperatures or alternatively to catalyze the reaction through the use of precious metals. [37] [38] However, the cost and availability of novel materials and/or precious metal catalysts must be considered.

Recently, Bloom Energy, a start-up based in Sunnyvale California, has attracted substantial media attention and a handful of initial investors. Their SOFC technology is based on research

---

Energy Laboratory, NREL/SR (2006): 620-38771

[35] A. Boudghene Stambouli, E. Traversa. "Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy." Renewable and Sustainable Energy Reviews, Volume 6, Issue 5, October 2002, Pages 433-455

[36] Kee, RJ.,Zhu H., Goodwin DG., "Solid Oxide fuel cells (SOFC) with hydrocarbon and hydrocarbon-derived fuels". Colorado School of Mines. <http://www.bloomenergy.com/products/resources/>

[37] High-Performance Ultrathin Solid Oxide Fuel Cells for Low-Temperature Operation Hong Huang, Masafumi Nakamura, Peichen Su, Rainer Fasching, Yuji Saito, and Fritz B. Prinz, J. Electrochem. Soc. 154, B20 (2007)

[38] Y. J. Leng, S. H. Chan, S. P. Jiang, K. A. Khor, Low-temperature SOFC with thin film GDC electrolyte prepared in situ by solid-state reaction, Solid State Ionics, Volume 170, Issues 1-2, 14 May 2004, Pages 9-15

originally carried out for the Mars Land Rover[39]. Bloom's solutions to the general challenges of SOFC are innovative, and promise a price competitive source of reliable local power generation. Currently their single product, the BloomBox Energy Server, is a 100 kWhr unit that can accept natural gas and biofuels. A single unit has a quoted price of $7-800,000 and a quoted operational lifetime of 10yrs. The operating temperature is over 700 C, but the system uses no precious metal catalysts[40]. In order to address reliability and degradation due to thermal stress, BloomBox uses a redundant array of modular fuel cells. Essentially, if a single fuel cell "stack" degrades after prolonged use, the system has additional fuel cell stacks to augment the failed unit.

Bloom Energy has shipped these 100 kwhr units to a handful of investors including eBay, Google, and SafeWay[41]. While these companies report energy savings, actual figures on reliability, performance, maintenance cost, and uptime are not disclosed. Given the major technical and scientific challenges associated with SOFC, these figures, in addition to the production costs, are the crucial figures for the long-term market viability of BloomEnergy.

---

[39] "About Us." Bloom Energy.< http://www.bloomenergy.com/about/company-history/ > Dec 8,2010.

[40] "ES 5000 Energy Server Data Sheet". Bloom Energy. http://www.bloomenergy.com/products/data-sheet/ Dec 8,2010

[41] "Customers" Bloom Energy. http://www.bloomenergy.com/customers/ Dec 8,2010.

2 Cost Competitiveness Analysis

2.1 Common Input Factors Adopted

2.1.1 Discount Rate

Constant-dollar and real-discount rate are adopted for the analysis. According to the Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Program given by Office of Management and Budget, a real discount rate of 7%[42] is adopted in base-case and 3% is adopted for low-cost case, 10% for high-cost case.

2.1.2 Policy Incentives

Policy drivers have been extremely important for the growth of renewable energy. The single most important policy driver, a 30% Business Energy Investment Tax Credit (ITC) from the federal government, is assumed. For offshore wind, a 10 yr production tax credit of 2.1¢/kWh is applied. For rooftop solar panels an additional 30% Business Energy Investment Tax Credit (ITC) from the state of Illinois is assumed.

2.2 Offshore Wind Cost Competitiveness Analysis

2.2.1 Assumptions

Project Size

The installed offshore wind projects worldwide from 1991-2009 have average name-plate capacities of 55 MW. However, many countries are expressing serious interest in employing offshore wind technologies. According to Renewable UK, the proposed projects have an average name-plate capacity of 293 MW. The five biggest U.S. offshore wind development projects have capacities over 300 MW. Our LCOE analysis assumes that Chicago will follow this trend to develop larger offshore wind farms. To reflect this we adopted a 300 MW nameplate capacity.

Initial Installed Cost of Capital

Initial capital costs (ICC) of offshore wind plants commissioned between 1991 and 2006 ranged from $1,300/kW and $2,800/kW. Beginning in 2007, the costs increased. Capital costs of projects commissioned between 2007 and 2009 ranged from $2,500/kW and $5,800/kW. The estimated average capital cost for proposed U.S. projects in 2010-2015 was $4,191/kW[43]. Hence, the base-case scenario adopts the $4,191/kW figure, the high-cost case adopts a figure of $6,375/kW and the low-cost case adopts $2,125/kW.

Capacity Factor

Empirical data collected from projects built in 2008 shows that capacity factors range from 16.6% to 43.5%. Typical national capacity factors during 2004-2008 ranged from 30 to 35% [44]. To

---

[42] (1992) Memorandum for Heads of Executive Department and Establishments: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. Office of Management and Budget.

[43] Musial W., Ram B. (2010) Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers. National Renewable Energy Laboratory

[44] Wiser, Ryan. (2010). 2009 Wind Technologies Market Report. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory.

reflect this we chose high capacity factor of 43.5%, a base-case capacity factor of 32.5% and a lowest capacity factor of 16.6%.

Operations & Maintenance Cost

The operations and maintenance (O&M) costs dropped from $32/MWh in 1980s to $22 MWh in 1990s and to $9/MWh in 2000s. This drop is attributed to technological advancements[45]. Nevertheless, as the turbine ages, O&M costs increase due to increased component failure. Thus in the estimation of O&M cost, we assume that starting at $9/MWh the O&M cost doubles every 10 years. Because the fluctuation of O&M is comparatively small, $0.027/MWh, $0.018/MWh, and $0.0083/MWh are adopted by high-cost case, base-case and low-cost case.

2.2.2 Analysis

Based on these assumptions, the LCOE is calculated by dividing the discounted lifetime cost by the discounted lifetime electricity generation. In the low-cost case the ICC and O&M costs were half the base-case costs. **In this case the LCOE of off shore wind reached $0.089/kWh which is cost competitive with coal**.

The sensitivity analysis is carried out the same way except the policy incentives are assumed to be zero. **In the low-cost case, the ICC is a quarter of the base-case resulting in an LCOE of $0.092/kWh which is also cost competitive with coal.**

The sensitivity analysis reveals that to be cost competitive with coal, offshore wind technology must improve its cost efficiency by 200% with policy support and 400% without policy support.

Base-Case with Policy Incentives

Assumptions	
Project Size (kW)	300,000
Initial Installed Capital (**ICC**) ($/kW)	4250
Annual Net Capacity Factor (%)	0.48
Operation & Maintenance Cost(**O&M**) ($/kWh)	0.018
Availability (%)	0.9
Discount Rate (%)	0.07
Productive Years (Yr)	20
Degrading (%)	0.005
Investment Tax Credit(**ITC**) (%)	0.3
Production Tax Credit (**PTC**)($/kWh 1st 10 yrs)	0.021
Levelized Replacement Cost(**LRC**) (Yr/total plant)	5000

---

[45] Wiser, Ryan. (2010). 2009 Wind Technologies Market Report. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory.

Decommissioning Cost (**DC**) ($/plant)	326300
Levelized cost of electricity ($/kWh)	**0.192833144**

High-Cost Case with Policy Incentives

Assumptions	
Project Size (kW)	300,000
Initial Installed Capital (**ICC**) ($/kW)	6375
Annual Net Capacity Factor (%)	0.48
Operation & Maintenance Cost(**O&M**) ($/kWh)	0.027
Availability (%)	0.9
Discount Rate (%)	0.07
Productive Years (Yr)	20
Degrading (%)	0.005
Investment Tax Credit(**ITC**) (%)	0.3
Production Tax Credit (**PTC**)($/kWh 1st 10 yrs)	0.021
Levelized Replacement Cost(**LRC**) (Yr/total plant)	5000
Decommissioning Cost (**DC**) ($/plant)	326300
Levelized cost of electricity ($/kWh)	**0.295437102**

Low-Cost Case with Policy Incentives

Assumptions	
Project Size (kW)	300,000
Initial Installed Capital (**ICC**) ($/kW)	2125
Annual Net Capacity Factor (%)	0.48
Operation & Maintenance Cost(**O&M**) ($/kWh)	0.0083
Availability (%)	0.9
Discount Rate (%)	0.07
Productive Years (Yr)	20
Degrading (%)	0.005
Investment Tax Credit(**ITC**) (%)	0.3
Production Tax Credit (**PTC**)($/kWh 1st 10 yrs)	0.021
Levelized Replacement Cost(**LRC**) (Yr/total plant)	5000
Decommissioning Cost (**DC**) ($/plant)	326300
Levelized cost of electricity ($/kWh)	**0.089529186**

Sensitivity Analysis with Policy Incentives

Scenario	**Initial Installed Capital Cost ($/kW)**	**O&M Cost ($/MWh)**	**LCOE ($/kWh)**
High-Cost	6,375	0.027	**0.295**
Base-Case	4,250	0.018	**0.193**
Low-Cost	2,125	0.0083	**0.089**

Sensitivity Analysis without Policy Incentives

Scenario	**Initial Installed Capital Cost ($/kW)**	**O&M Cost ($/MWh)**	**LCOE ($/kWh)**
High-Cost	6,375	0.027	**0.430**
Base-Case	4,250	0.018	**0.287**
Low-Cost	2,125	0.0083	**0.144**
	1,300	0.0083	**0.092**

2.3 Rooftop Thin Film Solar Cost Competitiveness Analysis

2.3.1 Assumptions

To analyze the performance of PV panels for Chicago's climate, we used the System Advisor Model (SAM) provided by the National Renewable Energy Laboratory. SAM combines geographic data and model parameters of specific panels in order to simulate real-world performance. We chose to analyze *United Solar Ovonic PVL-144*, a thin film amorphous silicon panel with a simulated efficiency of 6.57%.

Pricing

The current retail rate for the laminate is $3.45/W.[46] Inverter pricing was held at the current, and relatively stable, industry price index of $0.72/W.[47] Balance of system and installation costs were left at default values of $1.31 and $1.06 respectively.[48] The final installed cost per capacity is $8.52/W. Maintenance costs were also left at default values of $200/year and $0.25/kw-yr which are largely driven by the inverter.

System Setup

We assume the tilt angle of the panel to be 0 degrees giving a conservative estimate of energy production. The system size was limited to an area of 24.2 m^2 corresponding to a capacity of 2.5kW. System degradation was set at 0.8% a year, which follows the specified output levels according to the warranty.

---

[46] "Uni-Solar Solar Laminate PVL-Series 144 Watt." *Affordable Solar - Solar Panels, Kits, Residential Solar , Inverters, Charge Controllers*. Web. 03 Dec. 2010. <http://www.affordable-solar.com/uni-solar-laminate-pvl-Series-144-watt.htm>.

[47] "Inverter Prices." *Solarbuzz | Solar Energy Industry Research and Consultancy*. Web. 03 Dec. 2010. <http://www.solarbuzz.com/Inverterprices.htm>.

[48] FAQs « Uni-Solar." *Uni-Solar*. Web. 03 Dec. 2010. <http://www.uni-solar.com/resource-center/document-center/faqs/>.

Financing

The standard SAM residential model assumes that 80% of the initial cost will be taken up as loans while 20% will be paid for up front. Interest rate for the loan is set at 4.85% over 25 year lifespan of the solar cell.

Subsidies

Two major subsidies are included in the cost calculation: a 30% federal tax credit for renewable energy sources restricted to residential installations[49] and a 30% Illinois state subsidy restricted to systems over 1kW[50].

Illinois statute states that utilities are not obligated to provide net metering past 1% of the previous years peak demand load[51], and hence net metering was not applied.

Assumptions	
Project Size (kW)	2.5
Initial Installed Capital (**ICC**) ($/kW)	8520
Annual Net Capacity Factor (%)	0.142
Operation & Maintenance Cost(**O&M**) ($/kWh)	0.25
Availability (%)	1
Discount Rate (%)	0.07
Productive Years (Yr)	20
Degrading (%)	0.8
Investment Tax Credit(**ITC**) (%)	0.6
Production Tax Credit (**PTC**)($/kWh 1st 10 yrs)	0.00
Fixed Maintenance cost $/Yr	200
Decommissioning Cost (**DC**) ($/plant)	0
Levelized cost of electricity ($/kWh)	**0.2737**

2.3.2 Analysis

The SAM model gives a **LCOE of $0.2737 / kWh with incentives** and a **LCOE of $0.5766 / kWh without incentives**. The system produces an initial annual average output of 1, 975 kWh.

The total potential for roof top solar power can be calculated by estimating the total rooftop surface area of Chicago. According to an EPA heat island study, approximately 27% of Chicago's total surface area is made up of roof space[52]. Assuming 27% penetration of the city's 590 km^2 of

---

[49] *DSIRE: DSIRE Home*. Web. 03 Dec. 2010. <http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US37F&re=1&ee=1>.

[50] *DSIRE: DSIRE Home*. Web. 03 Dec. 2010. <http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=IL05F&re=1&ee=1>.

[51] *DSIRE: DSIRE Home*. Web. 03 Dec. 2010. <http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=IL13R&re=1&ee=1>.

[52] "Urban Heat Island Pilot Project (UHIPP) | Heat Island Effect | U.S. EPA." *Urban Heat Island Pilot Project*

available roof space, the total potential for rooftop solar energy in Chicago is 14000 MW/hr.

The LCOE for PV with incentives is still significantly higher than the 10¢/kWhr target set by coal. Furthermore, our LCOE projections of 57¢c/kWhr are above the industry average of 46-59¢/kWh for distributed small-scale systems. The current LCOE values for a utility scale PV plant range between 28 and 42¢/ kWh which is much lower than the 46-59 ¢/kWh range for small-scale applications[53]. This concern is seen on a local level if we examine a comparison between our LCOE with incentives of 27.37¢/ kWh and the LCOE of a 10 MW PV plant in Pullman, which stands at 30.15 cents / kWh[54]. While the residential LCOE is slightly lower, it is important to keep in mind that the residential LCOE has an extra 30% initial investment incentive that is not available to commercial applications.

Current DOE predictions see PV technology reaching grid parity in sun abundant regions by 2013 with widespread parity being achieved by 2015[55]. With national grid parity falling between 14-15 ¢/kWh, the thin-film laminate system considered here will need to cut its costs by about 50% within the next 5 years to meet this projection. In some parts of the country, this may be a realistic goal. For example, if our model is run again replacing Chicago with Phoenix Arizona, we see an immediate LCOE drop to 19.66 ¢/kWh, with incentives. Specifically, in comparison to the LCOE of Fisk, in order for thin-film laminates and BIPVs to be competitive with coal, initial installed capacity costs must be reduced by 66%, in addition to similar decreases in O&M costs. Without incentives, a 83.9% reduction in initial installed capacity costs and a corresponding decline in O&M costs needs to occur.

Sensitivity Analysis with Policy Incentives

Scenario	**Initial Installed Capital Cost ($/kW)**	**O&M Cost ($/kWh) and $/Year**	**LCOE ($/kWh)**
Current	8,520	0.25, 200	**0.274**
Cost Competitive with Coal	2,910	0.09, 68	**0.093**

Sensitivity Analysis without Policy Incentives

Scenario	**Initial Installed Capital Cost ($/kW)**	**O&M Cost ($/kWh) and $/year**	**LCOE ($/kWh)**
Current	8,520	0.25, 200	**0.577**

(UHIPP). US Environmental Protection Agency, 2002. Web. 05 Dec. 2010. <http://www.epa.gov/heatisld/pilot/index.htm>.

[53] Komor, P. "Wind and Solar Electricity: Challenges and Opportunities." Pew Center on Global Climate Change 48 (2009).

[54] Stavy, Michael. "Grid Parity and the Cost of Solar (PV) Electricity at Exelon's Pullman Plant – GLG News." *Gerson Lehrman Group - The Expert Network*. 26 July 2010. Web. 05 Dec. 2010. <http://www.glgroup.com/News/Grid-Parity-and-the-Cost-of-Solar-(PV)-Electricity-at-Exelons-Pullman-Plant-49678.html>.

[55] Lushetsky, John. *Solar Energy Technologies Program*. Rep. US DOE, 10 Aug. 2010. Web. 5 Dec. 2010. <http://www1.eere.energy.gov/solar/pdfs/dpw_lushetsky.pdf>.

Cost Competitive with Coal	1,370	0.04, 32.2	**0.093**

2.4 Bloom Box Cost Competitiveness Analysis

Bloom Energy claims that the cost of energy for the BloomBox is 8-10¢/kwh assuming a 30% federal investment tax credit and a $2500/kw subsidy from the state of California. These figures were later "confirmed" by Lux research. [56]In an effort to check this figures, we independently calculated the levelized cost of energy (LCOE) for the BloomBox, making the same stated assumptions about federal and state tax credits, $7/MMBtu long term gas contract, and the quoted efficiency. We also assumed that the lowest stated price of $700,000 for a single 100kw unit included maintenance and installation costs, which are not explicitly stated. Additionally, we assumed the unit ran continuously for 10 years with no loss in efficiency. In order to ensure a consistent comparison of technologies we adopted a 7% discount rate. Given these assumptions we arrived at a fully subsidized cost of 12.9¢/kWhr. In order to obtain an LCOE in the 8-10¢/kWhr range claimed by Bloom and subsequently confirmed by Lux Research, the discount rate must be reduced 0%, yielding an LCOE of 9¢/kWhr. **Clearly, the assumptions required to reduce the LCOE to the claimed levels significantly distort the price competitiveness of Bloom Energy even in the heavily subsidized California energy market**.

2.4.1 Assumptions

Given the absence of reliable lifetime operating and maintenance figures and the obvious price challenges BloomBox faces even when assuming no additional maintenance costs, we opted instead to address the question:

"At what price and maintenance figures can BloomBox become price competitive in the Chicago market at 10¢/kWhr?"

To answer this question we will look at three cases. In each of following cases we assume:

1. 7% discount rate
2. 30% federal subsidy
3. 10 yr natural gas contract of $7/MMbtu
4. Continuous operation at stated capacity for 10 years
5. Target LCOE of 10¢/kWhr

2.4.2 Analysis

Case 1: Ideal reliability and performance with no additional maintenance

Assumptions: The maintenance and installation costs are completely reflected in the initial capital cost, and there is no degradation in performance over the 10-year lifetime. Given these assumptions, the price of a single 100 kW unit would be **$294,000, representing a 58% reduction in the lowest quoted price.**

Case 2: Ideal reliability, no additional maintenance, realistic degradation

Here we assume a 100% uptime, no maintenance, but a **4% degradation in performance every year**. The 4% degradation was adapted from optimistic projections for the degradation in SOFC

---

[56] Pupoli L. "Is Bloom Energy a Better Place Redux?" <http://www.luxresearchinc.com/blog/2010/02/is-bloom-energy-a-better-place-redux/> Web. 8 Dec 2010

performance in 2003, when the major technologies present in Bloom were developed and patented. This scenario represents the best-case scenario given the information Bloom provides. With these assumptions the price for a single unit would be **$213,000 representing a 70% price reduction from the lowest quoted price.**

Case 3: Moderate reliability, substantial maintenance costs, ideal performance

Given the reliability challenges posed by high temperature SOFC and the modular structure of BloomBox, we assume that every year **5% of the BloomBox will require replacement** and a **reduced uptime of 95%**. Given the substantial maintenance work in this scenario we assumed the unit operated with ideal efficiency. With these assumptions, the price for a single unit would be **$160,000, representing a 77% reduction in the lowest quoted price.**

Case 4: Good Reliability, moderate maintenance costs, low degradation

Here we assume an **uptime of 98%, a yearly replacement of 2% of the fuel cells**, and a **2% annual reduction is operating efficiency**. This scenario shows good performance in all of the areas where data is not available. With these assumptions, the **price for a single unit would be $195,000 representing a 72% reduction in price.**

In addition to the uncertainties in maintenance and lifetime performance, there is variability in the price of natural gas. A $1 uncertainty in the price per MMbtu corresponds to 0.7¢ uncertainty in the LCOE for any given scenario. However given the larger price barriers shown in the example cases, the uncertainty in the price of natural gas is not a limiting factor in the broad adoption of BloomBox.

3 Conclusions

For a subcritical coal plant like Fisk , the LCOE without carbon cost is ¢6.2/kWh and the LCOE with carbon cost is ¢9.3/kWh. To be cost competitive with coal while carbon cost is assumed, **offshore wind has to cut 50% of its ICC and annual O&M cost**; **rooftop solar panel has to cut 67% of its ICC and annual O&M cost; and bloom box has to cut ~70% of its ICC**.

Without assuming any policy incentives being carried out, to be cost competitive with coal while carbon cost is assumed, offshore **wind has to cut 75% of its ICC and annual O&M cost**; **rooftop PV has to cut 83.9% of its ICC and annual O&M cost**.

We have used an LCOE based cost competitiveness analysis to illustrate the fact that frontier technologies are far from being cost competitive comparing with coal. Significant R&D as well as industrial application are required for these technologies to make progress and improvement. During the growth, policy incentives play critical roles and the cost of carbon will facilitate the development of clean energies.

"Uni-Solar Solar Laminate PVL-Series 144 Watt." *Affordable Solar - Solar Panels, Kits, Residential Solar , Inverters, Charge Controllers*. Web. 03 Dec. 2010.

Cheyney, Tom. "NREL Confirms Spectrolab Solar Cell Hits New Conversion Efficiency Record of 4 .6% - Photovoltaics International." Photovoltaics International. 27 Aug. 2009. Web. 28 Nov. 2010. <http://www.pv-tech.org/news/_a/nrel_confirms_spectrolab_solar_cell_hits_new_conversion_efficiency_record_o/>.

Derbyshire, Katherine. "Wafer-based Solar Cells Aren't Done Yet | Renewable Energy News Article." Renewable Energy World - Renewable Energy News, Jobs, Events, Companies, and More. 9 Jan. 2009. Web. 02 Dec. 2010. <http://www.renewableenergyworld.com/rea/news/article/2009/01/wafer-based-solar-cells-arent-done-yet-54443>.

DSIRE: DSIRE Home. Web. 03 Dec. 2010. <http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US37F&re=1&ee=1>.

DSIRE: DSIRE Home. Web. 03 Dec. 2010. <http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=IL05F&re=1&ee=1>.

DSIRE: DSIRE Home. Web. 03 Dec. 2010. <http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=IL13R&re=1&ee=1>.

Garrad Hassan & Partners, Tractebel Energy Engineering, et al. (2001) Offshore Wind Energy Ready to Power a Sustainable Europe.

Kho, Jennifer. "Solar: Doing the Dirty." RedHerring.com ~ The Business of Technology. 8 Dec. 2006. Web. 02 Dec. 2010. <http://www.redherring.com/Home/20157>.

Komor, P. "Wind and Solar Electricity: Challenges and Opportunities." Pew Center on Global Climate Change 48 (2009).

Lushetsky, John. *Solar Energy Technologies Program*. Rep. US DOE, 10 Aug. 2010. Web. 5 Dec. 2010. <http://www1.eere.energy.gov/solar/pdfs/dpw_lushetsky.pdf>.

Margolis, R. "A Review of Pv Inverter Technology Cost and Performance Projections." National Renewable Energy Laboratory, NREL/SR (2006): 620-38771.

McCaffrey B. (2005) Wind Turbine Technology Overview. Global Energy Concepts.

Musial, W. D., C. P. Butterfield, et al. (2004). Future for offshore wind energy in the United States : preprint. Golden, CO, National Renewable Energy Laboratory.

Musial W., Ram B. (2010) Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers. National Renewable Energy Laboratory

"NREL: Dynamic Maps, GIS Data, and Analysis Tools - Solar Maps." National Renewable Energy Laboratory (NREL) Home Page. Web. 28 Nov. 2010. <http://www.nrel.gov/gis/solar.html>.

Offshore Design Engineering (ODE) Limited. (2007) Study of the Costs of Offshore Wind Generation: A Report to the Renewables Advisory Board & DTI.

Rohatgi, A., A. Ristow, and V. Yelundur. "Cost and Technology Roadmaps for Cost-Effective Silicon Photovoltaics." (2003).

"Inverter Prices." *Solarbuzz | Solar Energy Industry Research and Consultancy*. Web. 03 Dec. 2010. <http://www.solarbuzz.com/Inverterprices.htm>.

"Solar Cell Technologies." Solarbuzz | Solar Energy Industry Research and Consultancy. Web. 03 Dec. 2010. <http://www.solarbuzz.com/Technologies.htm>.

Stavy, Michael. "Grid Parity and the Cost of Solar (PV) Electricity at Exelon's Pullman Plant – GLG News." *Gerson Lehrman Group - The Expert Network*. 26 July 2010. Web. 05 Dec. 2010. <http://www.glgroup.com/News/Grid-Parity-and-the-Cost-of-Solar-(PV)-Electricity-at-Exelons-Pullman-Plant-49678.html>.

Swanson, R. M. "The Promise of Concentrators." Progress in Photovoltaics: Research and Applications 8.1 (2000): 93-111.

"Urban Heat Island Pilot Project (UHIPP) | Heat Island Effect | U.S. EPA." *Urban Heat Island Pilot Project (UHIPP)*. US Environmental Protection Agency, 2002. Web. 05 Dec. 2010. <http://www.epa.gov/heatisld/pilot/index.htm>.

"FAQs « Uni-Solar." *Uni-Solar*. Web. 03 Dec. 2010. <http://www.uni-solar.com/resource-center/document-center/faqs/>.

Vidal, John. "Engineers Race to Design World's Biggest Offshore Wind Turbines | Environment | The Guardian." *Latest News, Comment and Reviews from the Guardian | Guardian.co.uk*. The Guardian, 26 June 2010. Web. 5 Dec. 2010. <http://www.guardian.co.uk/environment/2010/jul/26/offshore-turbine-britain>.

Wiser, Ryan. (2010). 2009 Wind Technologies Market Report. Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory.