An Analysis of the Current Costs and Future Prospects of Solar Photovoltaic Electricity

by

Alexander Tung-Qiang Wong, B.S.

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An Analysis of the Current Costs and Future Prospects of Solar Photovoltaic Electricity

APPROVED BY

SUPERVISING COMMITTEE:

Supervisor: ______________________________

David J. Eaton

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David B. Spence

DEDICATION

To my family, for putting up with me all these years; I still wonder how.

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I would like to thank David Eaton for supporting my numerous research interests, allowing me to make mistakes, and helping me learn from them. I would also like to thank Dr. Spence, Dr. Jablonowski, and Dr. Groat for sharing their knowledge. Finally, I would like thank my friends: it was a great ride, see you in the real world.

ABSTRACT

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The solar photovoltaic industry has many barriers to overcome before it can become a technically and economically competitive generation source including (1) lowering true generation costs, (2) decreasing reliance from government subsidies, and (3) developing a suitable energy storage solution. Current unsubsidized costs of electricity from solar photovoltaic sources range from 24.0 to 58.3¢/kWh. Subsidies bring the generation costs down to as low as 11¢/kWh, competitive with the average retail price of electricity in certain parts of the country. Current subsidy policies used to encourage technology development may generate more profits rather than research and innovation. The most optimistic predictions for solar photovoltaics include a convergence of a steep and prolonged rise in the cost of fossil-fuel based generation with a deep and prolonged decrease in the cost of photovoltaic generation by 2019. Deviation from optimal conditions will prolong the delay the crossover until at least 2021 and possibly beyond 2030. The development of a solution to store excess electricity when the sun is available during the day for use at night is necessary for photovoltaic electricity to become a dominant generation source.

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GLOSSARY

PV: photovoltaic

PPA: Power purchase agreement

Kilowatt-hour (kWh): a measure of electricity defined as one kilowatt of power for a period of one hour

Megawatt-hour (MWh): One thousand kilowatt-hours

Levelized cost of energy (LCOE): the nominal cost of building and operating a generating plant over its economic life, converted to equal payments per kilowatt-hour

Introduction

Visions of cheap renewable energy are a common theme in fiction. For example, John Galt produced an engine capable of using the static electricity in the ambient air as its main fuel source in Ayn Rand's *Atlas Shrugged*. He created a machine that tapped an inexhaustible resource, which in turn could be used as the motor to drive cars, boats, and airplanes, create electricity, and ultimately drive economic development. The cost of producing electricity from a power plant equipped with Galt's technology was quite literally too cheap to meter. Humans have a romantic ideal about deriving its energy supply from an infinite and clean fuel source, whether it is the sun, wind, ocean tides, or heat buried deep beneath the Earth's surface. The sun has been used for centuries to heat homes and water, provide energy for plants and, beginning in the 1950s, to generate electricity. Electricity derived from solar energy has a number of benefits unavailable to fossil fuel generators. Unlike coal, gas, or oil which produces damaging pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particular matter (PM), a kilowatt-hour of electricity from solar power results in exactly zero emissions; it is pollution-free. Fossil fuels also need to be found and extracted while the sun is available everywhere and has zero associated exploration and production costs. Since solar electricity production requires no fuel, it is shielded from fuel prices, which can be volatile. The price per kilowatt-hour of electricity stays constant throughout its economic life, excluding maintenance and repairs. It is said that the sun provides the Earth with more solar energy in one hour than human civilization uses in one year. The sun packs an energy supply so abundant that we humans could never dream about exhausting the resource. Society has since developed the technology to convert sunlight into electricity by using photovoltaic (PV) cells or creating steam from concentrated solar power (CSP) to drive turbines. For all of its advantages, solar power has limits. The sun is only available 40 percent of the time in sunnier locations. Another problem with solar power today is that unlike Mr. Galt's machine, our ability to harness the sun's energy is not too cheap to meter rather solar photovoltaics are too expensive to use in many applications.

This thesis analyzes the costs of solar power today and estimates how far solar technologies must advance in order to compete with the mix of electricity generators used today. The results were obtained from both a literature review and an analytical model. Among the topics explored are the issues of subsidies to the solar industry and externality costs resulting from fossil fuel generation. This report analyzes the solar industry behind the exaggerations erected by pundits on either side of the subject to help guide the reader to answer the following question: will solar power ever become the dominant energy source or will it always be known as the energy source of the future?

The basics of solar photovoltaics

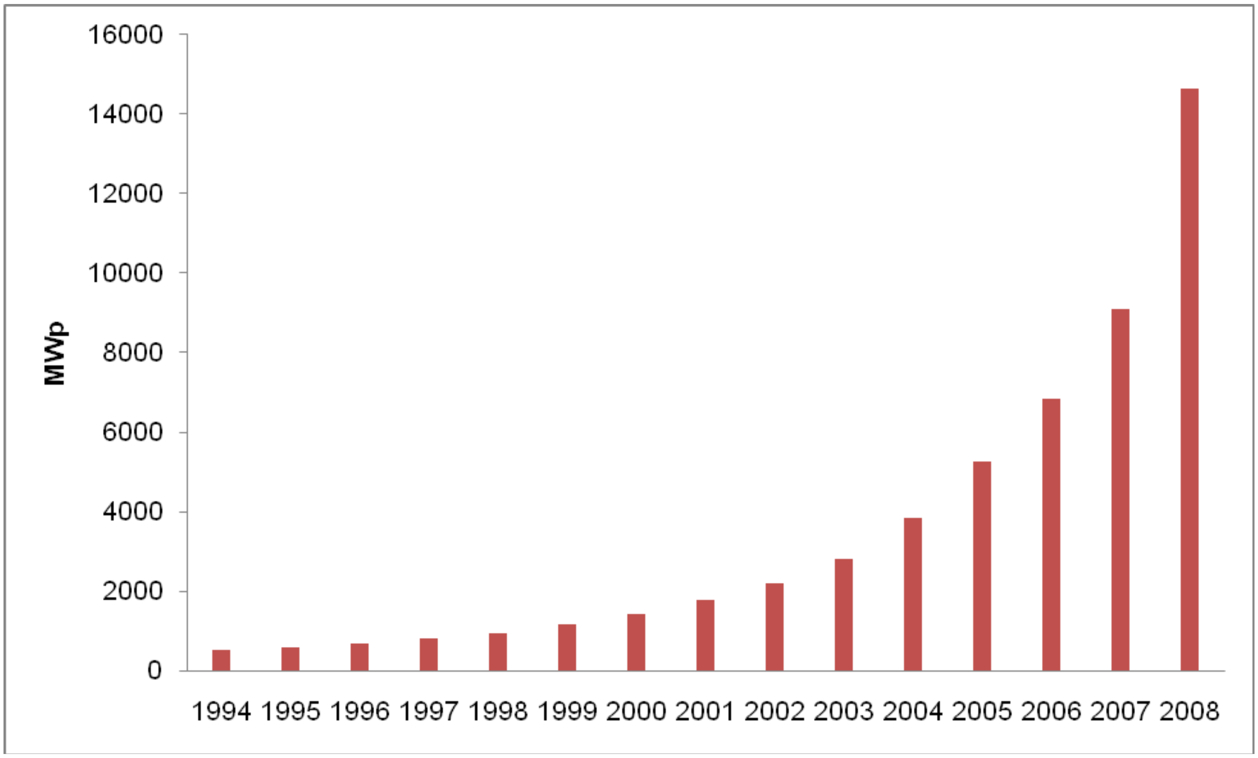
Two main types of solar energy are in development today. Photovoltaic (PV) cells are a solid-state generation platform with no moving parts that produces electricity using an electrochemical process. The two kinds of PV cells are silicon based and thin film. Silicon cells can reach a real-life efficiency of about 16 percent while thin film cells have an efficiency of 10.6 percent at the moment (Stevenson, 2008). Higher efficiencies translate into smaller cells, fewer raw materials, fewer engineering requirements, and cheaper overall systems. Silicon cells are a very mature technology and have been in development for over 50 years, while thin film technologies have just recently reached the commercial phase. The technology is still in development and has room to improve to its theoretical maximum efficiency to 20 percent (Stevenson, 2008).

The other type of solar power used commercially to generate electricity is concentrated solar power (CSP), which uses mirrors to focus sunlight onto a specific area. The sunlight heats a fluid which is used to create steam and drive a turbine that generates electricity. One example is the Solar Tres power tower will use molten salt as the heat transfer fluid which is heated to 1,050°F.

The hot salt will be used to turn water into steam, which will drive a steam turbine. The high heat capacity of the salt allows generation for up to 15 hours when there is no sunlight available (Martin, 2007). The other CSP technology currently in operation is the parabolic trough. Several other technologies are in development phase, but are not yet available on a commercial scale. Several CSP demonstration plants totaling over 350 MW were built between 1984 and 1990 in California. The original project sponsor, Luz International, went bankrupt in 1991, but these power plants continued to operate (Smil, 2005).

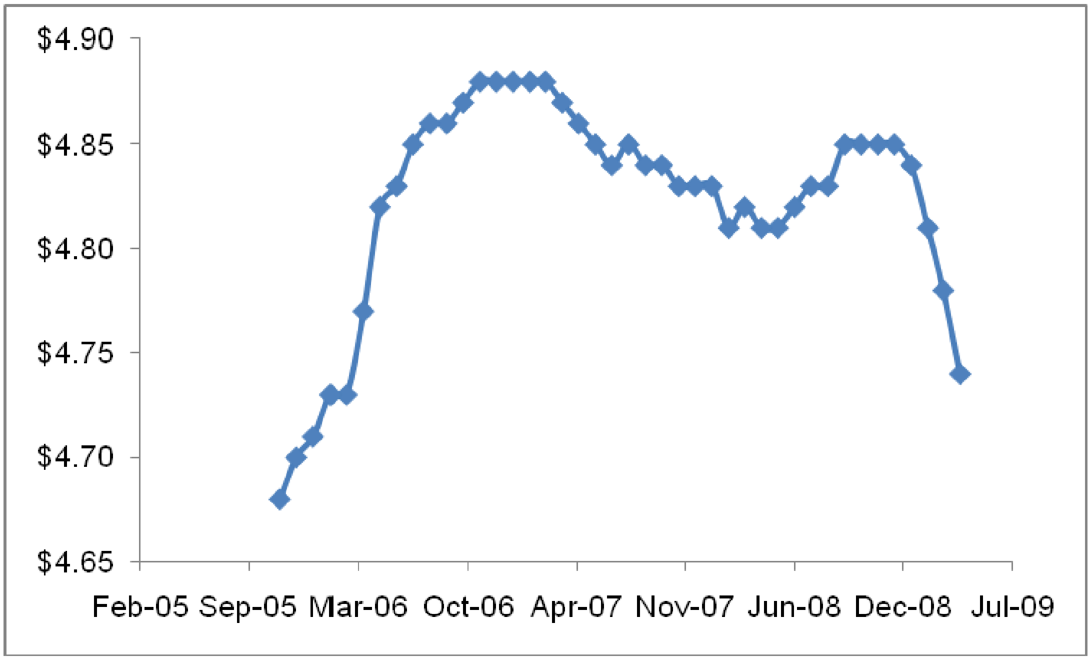
Solar generation capacity today consists mostly of silicon PV (92%). The solar power industry has recently experienced tremendous growth in PV capacity, averaging an annual growth rate of nearly 32 percent since 1998 and increasing over 15 times in size (see Figure 1) (EPIA, 2008). Since PV largely dominates the solar market, this thesis will focus on PV based solar power. The current cost of silicon cells average $4.74 per Watt (W) not including installation costs, but price per Watt fluctuates between $4.65 and $4.90 from 2005 to 2009 (see Figure 2).

Figure 1. Cumulative global PV capacity (1994-2007)



EPIA, 2008. Global Outlook for Photovoltaics until 2012: Facing a Sunny Future. Report, European Photovoltaic Industry Association, February 18. Available: http://www.epia.org/fileadmin/EPIA_docs/publications/epia/EPIA__MarketPublication_18feb.pdf

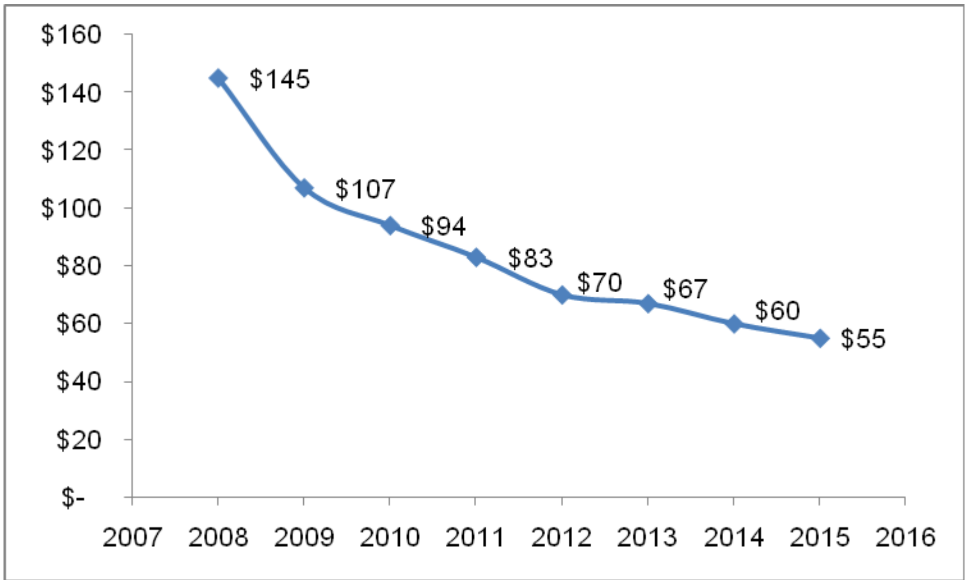
Figure 2. Solar module prices from 2005-2009



Solarbuzz, 2009. "Solar module retail price environment. Available: http://www.solarbuzz.com/ModulePrices.htm

The general trend of decreasing panel prices from 2001 to 2004 ended because of the increasing demand for solar panels. Higher demand has increased raw material and solar panel pricing since 2004. One of the key raw materials is polysilicon. Spot market prices of polysilicon rose from \$30/kg to over \$400/kg between 2004 and 2008. Long-term contract prices for 2008, however, averaged about \$165/kg (Figure 6) (Stevenson, 2008; New Energy Finance, 2008).

Figure 3. Long-term polysilicon contract price projection (2008-2015)



New Energy Finance, 2009. Presentation, New Energy Finance Global Insight Overview, China, March 19

Only 7 firms worldwide supplied the bulk of the polysilicon in 2007 (Arnoldy, 2008). Although silicon is one of the most abundant elements on Earth and used widely in the semiconductor industry, solar cells demand a higher quality of polysilicon. Solar cells require "6N" pure silicon which is 99.9999 (six nines) percent pure (Flynn, 2006).

Between 9-12 grams of polysilicon are consumed per Watt manufactured (Flynn, 2006; New Energy Finance, 2008; Swanson, 2007). Every dollar that polysilicon prices increases roughly equates to a 1¢/W increase in manufacturing costs. With the technology and manufacturing available today, a polysilicon cost of $30-165/kg can represent a cost of $0.27-$2.00 per Watt manufactured. Several new polysilicon supplies have come online in 2009, leading to lower polysilicon prices, which are expected to continue to drop (see Figure 3). Production could triple

2006 production levels by the end of 2009, easing the current polysilicon shortage, and potentially dropping the price of polysilicon significantly (Arnoldy, 2008).

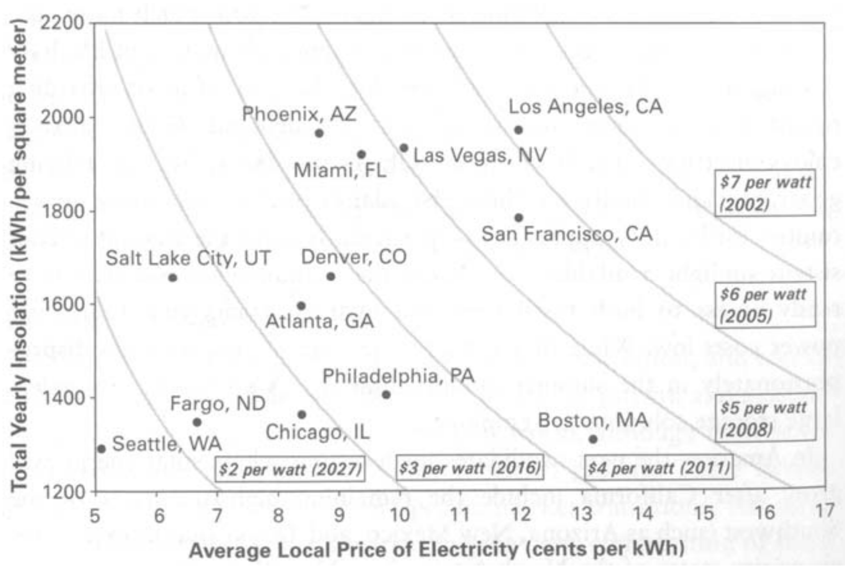
Non-silicon based PV manufacturers such as First Solar were not affected by this shortage. First Solar uses a cadmium telluride (CdTe) based thin film cell. Cadmium is a common byproduct of mining, so it is an available resource. Tellurium is costlier, but the amount of material deposited on thin film cells are only microns thick, lowering raw material costs. The company had a manufacturing cost of $1.14 per Watt in 2008 which it expects to lower to $0.70 per Watt by 2020 (Stevenson, 2008). Thin film panels are significantly cheaper to manufacture than silicon-based PV, but the efficiency of thin-film panels are also lower. The lower efficiency translates into larger installation areas for thin-film panels, resulting in higher installation and property costs. Thin-film technology is also less mature and less competitive than silicon PV, with one firm largely dominating the thin-film market.

Panel costs only contribute to a portion of photovoltaic systems. The other cost components include site assessment, site engineering, installation, grid hook-up, and inverter costs which account for at least 40 percent of the total system cost. An inverter is required to covert the DC power generated by PV panels to the AC power that comes out of wall outlets. Inverters cost about 70¢ per continuous Watt of capacity (Solar Buzz, 2008). Aside from high capital expenditures, solar panels have low operational costs. There are no fuel costs and maintenance costs can be negligible. Several utility scale PV installations in Arizona surveyed over a 3 year period and found that maintenance costs averaged 0.16 percent of the original capital investment (Sandia, 2005). A PV system with capital costs of $7,000/kW then has annual fixed costs of $11.20/kW. The EIA made a similar estimate, with fixed costs of $11.68/kW (EIA, 2009).

Modeling solar energy costs

One barrier to determining the current costs of solar power was that the data available were not necessarily reliable. One solar projection published by NASA and the DOE appeared to be too optimistic (see Figure 4).

Figure 4. Solar energy cost competitive projections



Bradford, T., 2006. Solar revolution: the economic transformation of the global energy industry. MIT Press. Cambridge, Massachussets

This graph indicates that PV is cost competitive at $6/W in Los Angeles with a LCOE of slightly more than 12¢/kWh. A simple back-of-the-envelope calculation demonstrates that these isocurve projections cannot be correct. A 1 kW array at $6/W has a total cost of $6,000. Los Angeles receives 2,000 hours of sunlight per year, producing 60,000 kWh of electricity over a 30 year period. Assuming that the system incurs no further costs, dividing total costs by total electricity production reveals a LCOE of 10¢/kWh. The calculation underestimates the true LCOE, since it values a 2039 dollar the same as a 2009 dollar. It also ignores expenses incurred from inflation, taxes, operation, and maintenance. A rudimentary discounted cash flow using a nominal 2 percent discount rate, less than the historical rate of inflation, raises the LCOE to 13.1¢/kWh (Financial Trend Forecaster, 2009). How much more would the LCOE increase once the other fiscal terms were included? The unrealistically optimistic projections currently published prompted the author to develop a model that projected more realistic end-generation costs.

An analytical Excel-based analytical model was developed to determine the current costs of solar power today and to "back into" data when there were gaps. The model predicted solar energy costs based on input data such as capital, operating, and maintenance costs, as well as capacity factor. The methodology used was based on the assumption that every technology has a set of unique parameters. For example, a PV system in Los Angeles, CA operates at peak capacity for about 2000 hours per year, about a 23 percent capacity factor (Solar Buzz, 2009). PV systems should therefore not operate at significantly greater capacity factors than 23 percent. The final results were used to determine whether the cost or performance estimates were both technically feasible and in-line with the rest of the industry. One of the difficulties encountered with the model was actually compiling a complete dataset including all relevant cost and performance data regarding a particular project. Data were scarce or not provided by a reliable source, resulting in many incomplete data sets. For example, companies were willing to provide the end-cost of electricity generation without providing any input data. One example is the claim that Sunrgi has the technology to produce electricity for 5.0¢/kWh (Sunrgi, 2009). The model was able to interpolate the capital cost of the project within a reasonable margin of error.

Sunrgi claims that its system produces about 175 percent of the electricity of a standard fixed PV system of the same nameplate capacity. One of the assumptions was that the system would be placed in a sunny area, such as Los Angeles, raising the capacity factor from 23 percent to about 40 percent (Sunrgi, 2008). The model calculated that the total system costs need to be below $2,500/kW to produce electricity at 5.0¢/kWh. The same methodology was used to determine the costs of a similar CPV system installed by SolFocus, a direct competitor of Sunrgi, of $10,000/kW (Cheyney, 2009). Sunrgi's prediction that it can install a similar solar generation station at just 25 percent of the cost of SolFocus warrants deeper analysis into the difference between the companies and technologies.

The model also serves a dual-purpose; it ensures a fair, apples-to-apples comparison between the competing technologies and projects. While some parameters were unique to each project (such as capacity factor, heat rate, variable costs, or fixed costs), others parameters were held constant throughout the analysis, except for residential solar systems which were given tax rates of 0 percent (see Table 1).

Table 1. Assumptions used in the LCOE model

Discount rate	10%	Loan period	15 years
Interest rate	5%	Tax rate	30%
Inflation rate	3%	Debt fraction	80%

The capital cost, operating expenses, and capacity factor of each technology is unique to each project. Fiscal terms were held constant since adjusting the discount, interest, and tax rate, can severely affect its valuation. Table 2 compares the generation cost of the same project under different financing structures.

Table 2. The effect of altering project financing structures on electricity generation costs

Conergy SinAn Project	**Scenario 1**	**Scenario 2**
Debt fraction	50%	80%
IRR	10%	10%
LCOE	48.2¢/kWh	42.7¢/kWh
Difference	5.5¢/kWh (12.8%)	

The Conergy SinAn project at 50 percent debt financing and an internal rate of return (IRR) of 10 percent has a LCOE of 48.2¢/kWh. Changing the debt financing to 80 percent lowers the LCOE to 42.7¢/kWh, a rather significant difference of 5.5¢/kWh (12.8%). The comparison was performed to demonstrate that project economics can be manipulated by changing fiscal terms. To conduct a fair cost comparison across different projects and technologies, an analyst should use common assumptions to assess each project. The model used herein uses a consistent methodology to value both solar and fossil fuel generators. If a solar generator is undervalued, the model will similarly undervalue a fossil fuel generator. A survey detailing the parameters of 12 power plants was completed to roughly compare the costs of generation from various sources (see Table 3).

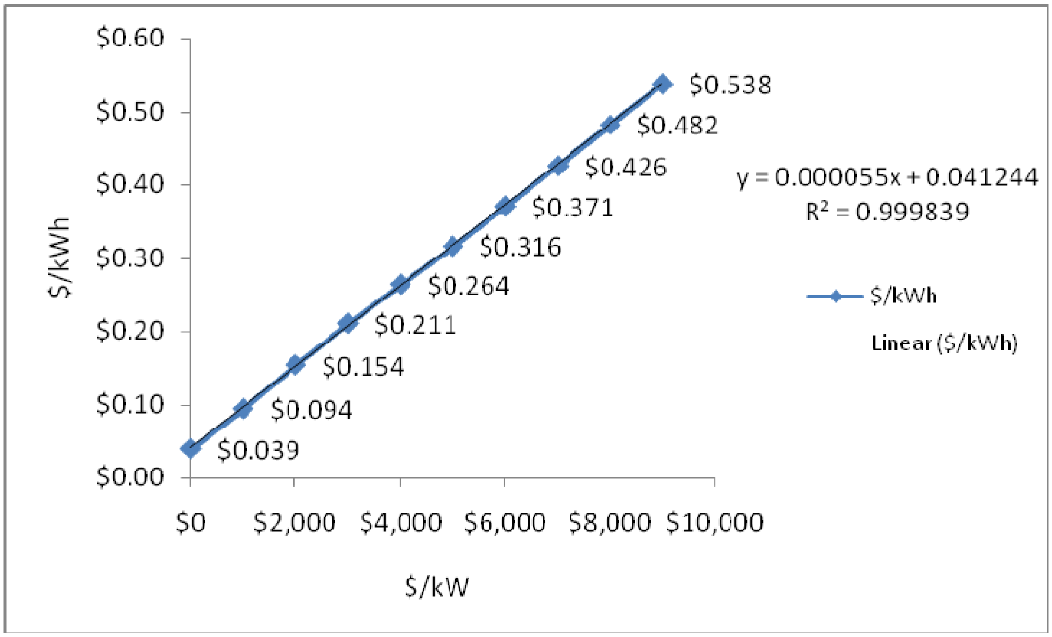
Table 3. Survey of capital costs and LCOE of various power projects

Name	**Type**	**Size (MW)**	**Year completed**	**Capital cost ($/kW)**	**Projected LCOE (¢/kWh)**
Solar Garden	Silicon PV	9.55	2007	8,848	58.4
SinAn	Silicon PV	19.6	2008	5,969	38.1
SkyPower	Thin film	19	N/A	4,189	45.1
Rote Jahne	Thin film	6	2007	4,667	49.8
SolFocus	CPV	10	2008	10,000	24
Austin home	PV	0.036	2009	8,000	48.2
Generic	SCGT	100	N/A	421	14.1
Generic	CCGT	100	N/A	621	5.3
Generic	Coal	800	N/A	2,058	4.9

For sources, see Appendix A

The survey of solar projects revealed levelized costs from 24.0 to 58.4¢/kWh. The residential retail rate of electricity from Austin Energy today is 6-11¢/kWh. The average cost of electricity in California, which has a reputation for high electricity costs, is 12.8¢/kWh (Austin Energy, 2008; EIA, 2009). Solar electricity costs between 2 and 10 times as much as electricity from the grid. The model projects that installed costs of PV systems must drop to about $2 per Watt before it becomes cost competitive with the grid (see Figure 5).

Figure 5. Variation of the levelized cost of solar power at various installed costs



The price projections are based on a 20 percent capacity factor which can be achieved in areas with dense solar resources such as Southern California or West Texas. Within the continental 48 states, California is most likely to reach cost competitiveness first because it has high quality solar resources and among the highest average retail electricity rates of 12.82¢/kWh (EIA, 2009). At the rates today, the costs of solar panels would need to drop 70 percent to $1,500/kW to reach cost competitiveness. Martin Green of the University of New South Wales predicts that the lower limit of silicon PV modules is $2,000/kW, making a system cost of $1,500/kW unattainable (Bradford, 2006). Notice that even with zero installed costs the LCOE is still 3.9¢/kWh. This cost is due to labor and maintenance. Inverters require replacement every 5-10 years (Bradford, 2006). The replacement cost of a 3 kW residential-size inverter would likely be close to $2,400.

Solar PV can also be installed as a distributed generator, meaning that its electricity is used at the point of generation. The benefit of distributed generation is that the electricity does not need to be transported to the end-user, eliminating transmission and distribution costs. Utility-scale projects, on the other hand, generally cannot be installed as distributed generation. There is simply not enough space available in populated areas to install large solar arrays, thus, the electricity will incur transmission and distribution costs. The main problem is that small scale distributed generation is more expensive than utility-scale applications. The average residential PV array in Austin averaged $8.80/W in 2007, while the cost of some utility-scale projects were as low as $4.20/W. Utility-scale projects can benefit from economies of scale, simplifying the engineering requirements of the installation site. Distributed rooftop generation, however, cannot achieve these cost savings, as each individual site has different solar resources depending on its orientation and shading, different roofing material, etc. Ultimately, each site must be assessed individually, leading to higher installation costs.

A Texas household that used 1,000 kilowatt-hours (1 megawatt-hour) had an electricity bill of $99-269 in June 2008 (Austin Energy, 2008). If the same household received all of electricity from solar PV instead, the electric bill would have cost $240-580. Despite its lack of cost competitiveness at the moment, solar power continues to grow at a very aggressive rate on a utility and residential scale.

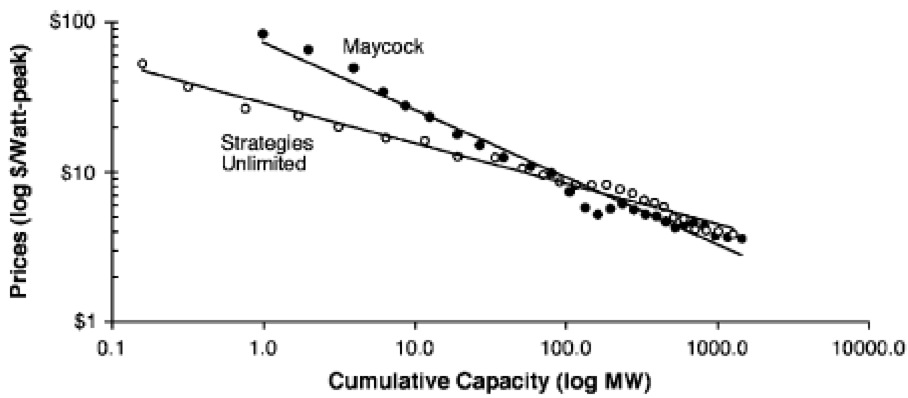
For the lack of available data on PV systems, the data for CSP generators is even scarcer. A study commissioned by NREL in 2003 projected that CSP technologies produce electricity at a cost of 9.9-12¢/kWh by 2004 and decreasing to 5.7-9.9¢/kWh in 2010 (NREL, 2003). The solar industry's lobbying group in the U.S., the Solar Energy Industry Association (SEIA) claimed in 2007 that CSP production costs were 10-14¢/kWh (SEIA, 2007). The average wholesale electricity price in Texas' Electric Reliability Council of Texas (ERCOT) and California markets were 6.34¢/kWh and 8.12¢/kWh, respectively, in 2008 (EIA, 2009). If solar generation technologies can supply electricity for less than the average wholesale price in several markets, economics dictates that solar power should be deployed on a rather large scale. Instead, solar capacity worldwide is less than 15,000MW, about half of Texas' peak summertime electricity demand. Electricity from solar generators is responsible for less than 1 percent of total generation in the U.S. and even less from CSP generators. The lack of current and reliable cost and performance data of led to the decision to omit CSP generators from this analysis.

The possibility of solar power becoming more economically viable due to rising costs of fossil fuel generation is explored later on in the thesis. The role of subsidies in this expansion is discussed in the next section.

The role of subsidies

Technologies that are deployed on a wide scale can achieve lower costs as technology advances, past experiences provide valuable lessons, and economies of scale are reached. Bruce Henderson of the Boston Consulting Group observed in several industries in 1960 that production costs declined as cumulative production increased. The concept of the experience curve was born. The solar industry uses the experience curve as the basis of many future cost projections. Two of the most widely known experience curve projections were made by Paul Maycock in 2002 and Strategies Unlimited in 2003 (see Figure 6).

Figure 6. Learning curve estimates provided by Maycock (2002) and Strategies Unlimited (2003).



Nemet, G.F., 2006. Beyond the learning curve: factors influencing the cost reduction in photovoltaics. Energy Policy 34(2006), 3218-3232

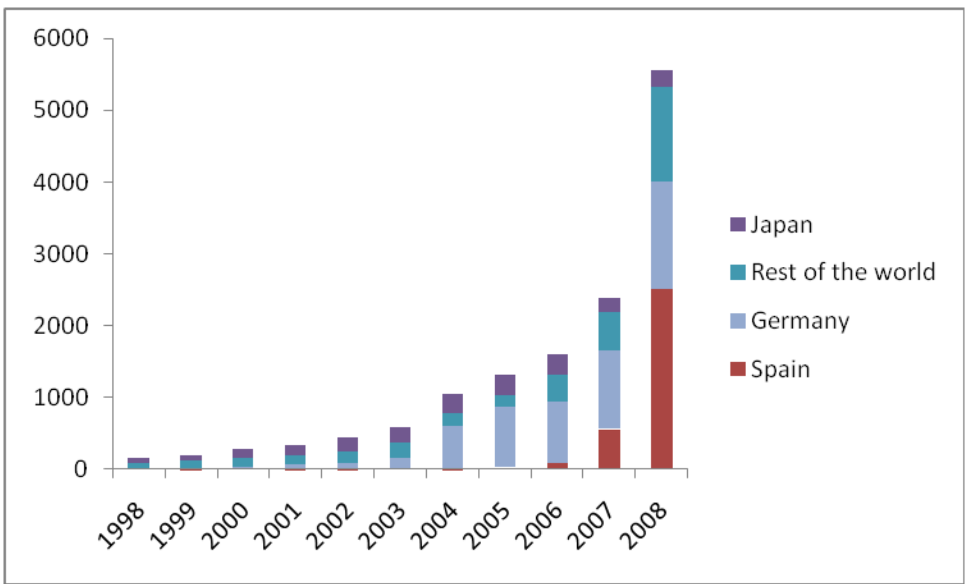
One of the main principles behind subsidizing the solar market is to accelerate cumulative production so solar technology advances along the experience curve more quickly. Using the experience curve to predict the rate at which production costs decline is not a perfect method. The quality of the learning curve may reflect the historical data used to plot the curve, but there is no inherent reason to believe that factors which affected costs in the past will recur in the future.

Particularly when cost reductions are graphed on a log-linear scale, the projections must assume very rapid cost reductions.

Both Maycock and Strategies Unlimited predicted learning ratios for solar power and produced two different results; Maycock determined a ratio of 0.26 and Strategies Unlimited a ratio of 0.17. The learning ratio is used to represent the percentage that production costs decline with every doubling of cumulative production. For example, if solar panels cost $50/W at a cumulative capacity of 1 MW, the costs would decline to $41.50/W when cumulative capacity reached 2 MW. Higher learning ratios result in more aggressive cost declines. Consider how long it would take for solar power to cross the $0.30/W threshold using the two different learning ratios at a constant annual growth rate of 15 percent. Maycock's learning ratio of 0.26 reveals that solar panels should reach the threshold in 2039 while the Strategies Unlimited ratio predicts 2067 (Nemet, 2006). The experience curve also unrealistically assumes that cost reductions continue indefinitely. Production will eventually reach a lower limit as raw materials and labor have associated costs. It can be agreed upon by all that the solar industry has not yet hit that lower limit, but it makes a great difference whether the threshold is $2/W as predicted by Green or $0.25/W. Despite the limitations associated with using the experience curve, this is the method used in this thesis to predict future prices for several reasons. First, it appears to be a method accepted by the solar industry. Richard Swanson, founder and president of solar manufacturer SunPower, uses this method himself in making projections of the solar industry (Swanson, 2007). And second, the experience curve is a straightforward and simple method that has generally correlated well to the actual cost evolution of declining production costs (Nemet, 2006).

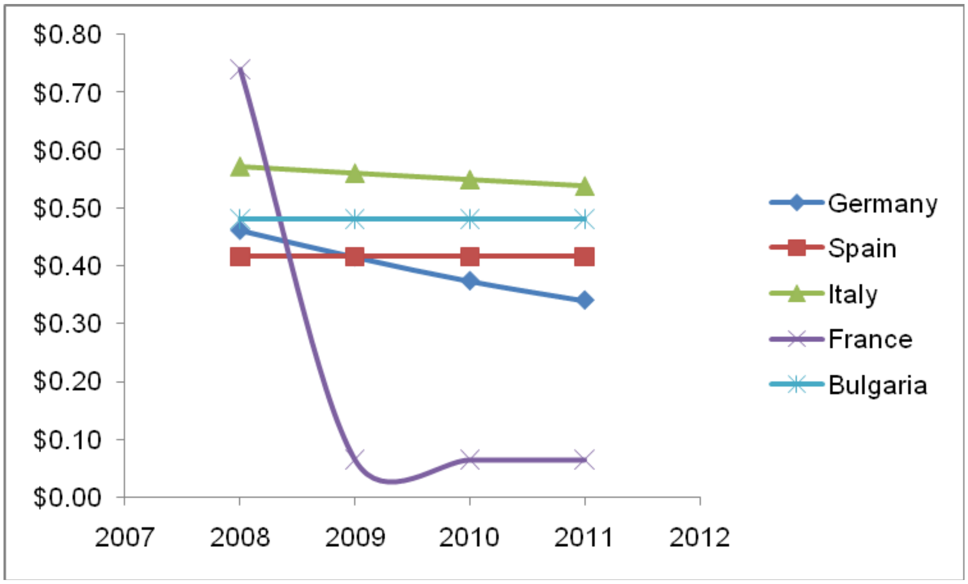
The installation of new solar generation capacity has recently been dominated by relatively few markets (see Figure 7). Japan was the market leader from the late 1990s until 2002, when it subsidized about 50 percent of the initial cost of a solar system. Japan gradually decreased its subsidies to 7 percent. By 2004 Germany became the new market leader. There is no doubt that subsidies have succeeded in increasing demand for solar energy. New solar installations grew by 25 percent in 2000, 38 percent in 2004, and 59 percent in 2008. Germany created one of the most successful policies to encourage development of the solar industry: the feed-in tariff (FiT). FiTs require that utility companies to purchase solar electricity at a set price. In Germany, the rate is between 45.5 and 61.1¢/kWh for a set period of time, usually 20-25 years (EPIA, 2009). Many credit the massive expansion of solar power to FiTs, which "have been responsible for the whopping growth of the PV industry in several European countries," along several other countries worldwide (Solar America Cities, 2008). The cost of the FiTs in Germany, however, are passed along to the ratepayers by the utility companies. As the share of solar generated electricity grew, so did the ultimate cost of the FiT. Its cost more than quintupled from €0.00087/kWh in 1998 to €0.0051/kWh in 2004 (Growitsch, 2005). The FiT currently adds about $1.60 onto the monthly electricity bill for German ratepayers (EPIA, 2009). Several other countries have adopted FiT policies, which contributed to the recent high growth in the industry. Spain grew from just a niche market in 2005, installing only 26 MW to the world leader in 2008 when over 2,500 MW was installed. The nations with the most generous subsidy policies generally experience the most growth (Figure 8).

Figure 7. New solar capacity by region (1998-2008)



EPIA, 2009. Global outlook for photovoltaics until 2013: Facing a Sunny Future. Report, European Photovoltaic Industry Association, April. Available: http://www.epia.org/fileadmin/EPIA_docs/publications/epia/EPIA__MarketPublication_18feb.pdf

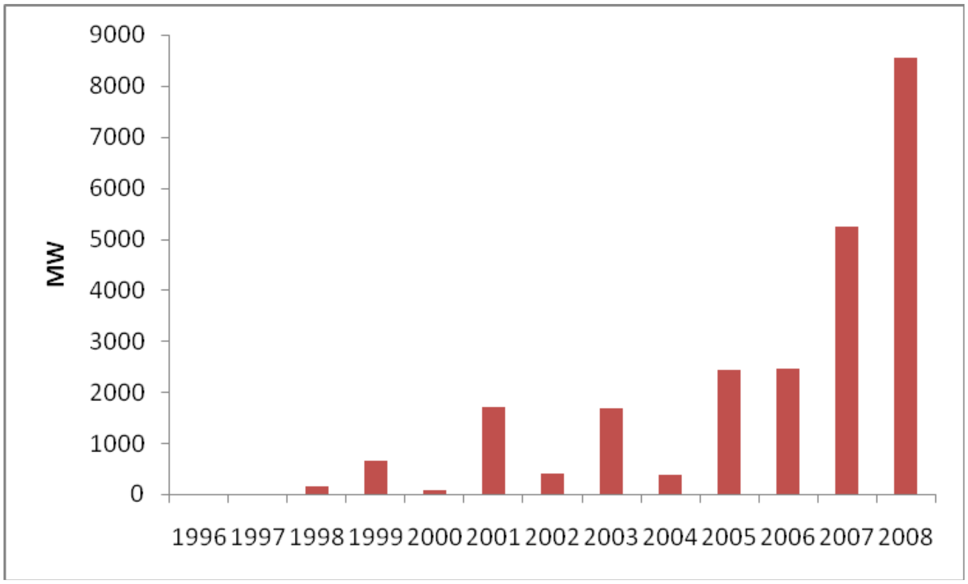
Figure 8. Planned European feed-in tariff policies (2008-2011)



EPIA, 2008. Overview of European PV support schemes. Report, European Photovoltaic Industry Association, December 17

Many nations now subsidize their solar industry, with some nations agreeing to pay upwards of 60¢/kWh of solar electricity for the next 2 decades. One can look towards the American wind industry to observe the role of subsidies on developing energy technologies. Instead of the ITC, the wind industry is given a production tax credit (PTC) of 1.9¢ for every kilowatt-hour generated (AWEA, 2009). The PTC expired in 1999, 2001, and 2003 before it was renewed by Congress. Expiration of the PTC was followed by a sharp decline in wind capacity additions the following year (see Figure 9).

Figure 9. Annual wind installed wind capacity (1996-2008)



AWEA, 2009. Annual wind industry report 2008. Report, American Wind Energy Association. Available: http://www.awea.org/publications/reports/AWEA-Annual-Wind-Report-2009.pdf

Following their wind counterparts, solar project developers are not installing capacity in the locations with the highest quality solar resources. There are far sunnier locations worldwide than Germany and Japan. Instead, the solar industry follows the subsidies. The Japanese solar market has "scarcely grown at all, or has even shrunk, since the national subsidies program ended," further reinforcing the fact that the solar industry is subsidy-dependent (Koot, 2008).

While subsidies have introduced additional renewable energy to the electricity market, the consequences of this economic distortion are not necessarily all positive. Tax and ratepayers are those responsible for paying for the more expensive generation sources. One particularly perverse consequence occurs in Texas during certain periods of the year when more wind energy is produced than the grid can absorb. Transmission lines become clogged and wholesale electricity prices plummet. The consequence is a phenomenon known as "negative pricing" when power is literally worth less than nothing; wind producers must pay customers to accept its electricity (Combs, 2008). Producers are willing to take losses on their electricity sales because the PTC is only received if electricity is delivered. Since wind energy has no marginal costs of production, the transaction is revenue positive as long as the sale price is above -1.9¢/kWh. It is even possible that such a transaction results in a double bonus for the wind producer: the sale is claimed at a loss in addition to the 1.9¢ in tax credits received. The beneficiaries are the wind producer and offtaker. Taxpayers, on the other hand, are subsidizing these kinds of transactions. The electricity supplied is not demanded or wanted by the market and it has a negative value. This particular example is a case where subsidy policies were not well executed and represent a tragedy of the commons when few parties benefit at the expense of many.

The solar industry does not escape from this fallacy of subsidies. In fact, all energy sources are subsidized to an extent. How do the subsidies of the solar industry compare with those received by conventional fossil fuel based generators? In absolute terms, the coal, natural gas, and nuclear industries receive much greater subsidies than the solar industry (see Table 4).

Table 4. 2007 electricity production subsidies.

Beneficiary	**Total generation (billion-kWh)**	**Subsidies and support ($million)**	**Subsidies and support (¢/kWh)**
Coal	1,946	854	0.044
Natural gas	919	227	0.025
Nuclear	794	1,267	0.159
Solar	1	14	2.43
Wind	31	724	2.37

EIA, 2007. Federal financial interventions and subsidies in energy markets: 2007. Report, U.S. Energy Information Administration.

The nuclear industry received nearly $1.3 billion in support in 2007, compared to 14 million by the solar industry. Solar generators however produced just 0.05 percent of the electricity of its coal counterparts and 0.12 percent of the electricity produced by nuclear in 2007. Once data are aggregated in terms of support per kilowatt-hour generated, solar energy disproportionately benefits from energy subsidies. The industry received 15 times more support per kilowatt-hour of electricity produced than nuclear power, which is commonly displayed as the poster child of energy subsidies. Table 4, however, only reflects subsidies given by the federal government and ignores support from state and local governments. Austin Energy, for example, offers a solar rebate of $3.75/W (maximum of $13,500) which pays up to 53 percent of a solar installation assuming system costs of $8/W (see Table 5).

The main federal policy supporting solar energy is the Investment Tax Credit (ITC), which rebated 30 percent and a maximum of $2,000 of the initial cost of residential and commercial solar installations until October 2008. A revised ITC was implemented in October 2008 which also allowed access to the ITC by utility companies and removed the $2,000 rebate limit (SEIA, 2008). Subsidies given out in 2009 will reflect new ITC policy and will probably significantly raise the amount of support received by the solar industry. Table 5 illustrates the effect of various subsidy policies on the cost of solar power.

Table 5. Comparison of residential Austin PV levelized costs under varying subsidy regimes ($8.00 per installed Watt, 3.6 kW system, 20 percent capacity factor)

Subsidy type	**Subsidy ($)**	**Subsidy ($/kWh)**	**LCOE (¢/kWh)**	**System cost ($/W)**	**Difference (%)**
Unsubsidized	N/A	N/A	39.8	8	0
30% ITC, $2,000 limit	2,000	2.6	37.2	7.44	7
30% ITC, no limit	8,640	11.2	28.6	5.6	30
Austin Energy $3.75/W, $13,500 max.	13,500	17.5	22.3	4.25	47
Combined ITC and AE rebate	22,140	28.7	11.1	1.85	77

Removal of the $2,000 limit on the ITC adds an additional $6,640 (332%) of support for this particular installation. Combining Austin Energy's solar rebate with the new ITC offered by the federal government subsidizes 28.7¢/kWh (72%) of the cost of solar electricity and results in a LCOE of 11.1¢/kWh. The subsidized cost of solar electricity is still only marginally competitive with grid-based electricity in Austin.

Analysis of the subsidies given to the fossil fuel generation industry was also performed. Burning fossil fuel generates harmful pollutants such as carbon dioxide, nitrogen oxides, and particulate matter. Generators are legally permitted to emit certain amounts of these pollutants that are known to cause harm to human health or the environment without financial penalty. The damages caused by these pollutants may include respiratory diseases to humans, damage to ecosystems, climate change and other environmental consequences. Ultimately, fossil fuel generators do not pay for most of these costs. These "hidden" subsidies are instead paid for by taxpayers. A methodology to quantify pollution costs from electricity generation sources was created by the European Commission's Externalities of Energy (ExternE) research project (see Table 6).

Table 6. Estimates of the cost of pollution

¢/kWh	**Coal**	**Gas**	**Solar PV**
Damage	0.98-1.71	0.01-.0.46	0.6
Avoidance	2.23-2.34	1.00-1.01	0.48
Total	3.21-4.05	1.01-1.47	1.08

Georgia Environmental Facilities Authority. 2006. Governor's energy policy council staff research brief: full cost accounting. Atlanta, Georgia. Available: http://www.gefa.org/Modules/ShowDocument.aspx?documentid=37

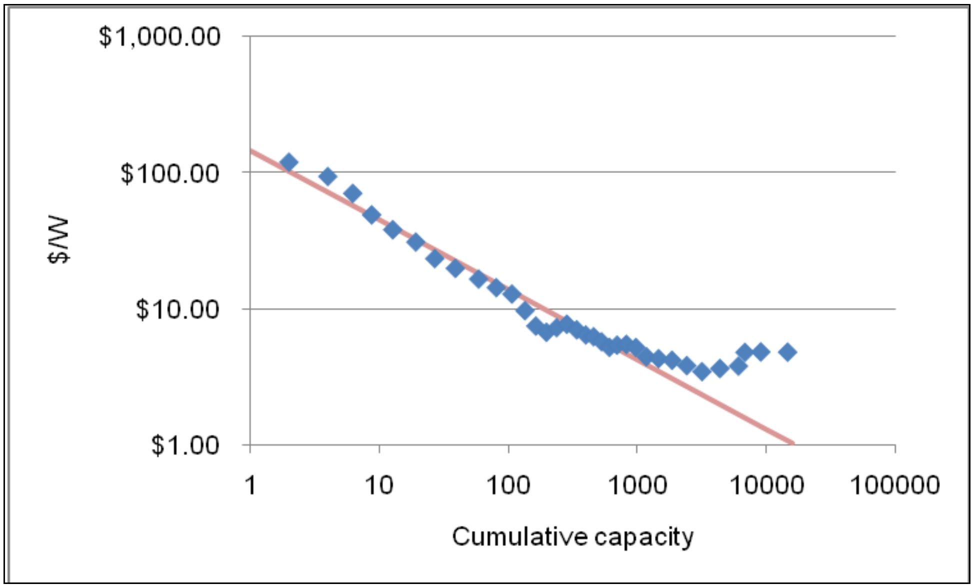
Health care and direct environmental damage are both classified as damage costs. Avoidance costs consist mostly of carbon dioxide mitigation. Friedrich and Bickel priced CO_2 around $21/ton in 2008 dollars. That cost may or may not represent the true cost of the impacts resulting from CO_2 emissions, but is debatable. An additional $220/ton CO_2 would need to be levied onto coal generation in order to match the 28.7¢/kWh subsidy that solar energy receives in Austin, TX. The breakeven carbon price for a SCGT is even greater since natural gas has a lower carbon content; the price would need to exceed $400/ton CO_2 to match the subsidy received by solar energy. The math behind these estimates are discussed in the section titled "Future energy prices"

A Greenpeace study that estimated the cost of coal fired generation at 160-240 RMB per ton of coal excluding the cost of climate change. Assuming an exchange rate of 7 RMB to the US dollar, the cost of coal increases by $1.20-1.79 per MMBtu (Katzer, 2007 and Yushi, 2008). Generation costs increase by 1.2-1.8¢/kWh which represents about 6 percent of the subsidy received by solar energy. While these costs may not necessarily represent the true costs of coal generation, the figures are in-line with the studies published by the Georgia Environmental Facilities Authority and Friedrich.

Classifying pollution costs as "hidden" subsidies results in average total subsidies of 1.27¢/kWh for natural gas and 3.67¢/kWh for coal power. The true unsubsidized cost of coal power then becomes 8.57¢/kWh, still less than solar power subsidies, which costs 23.4-58.4¢/kWh.

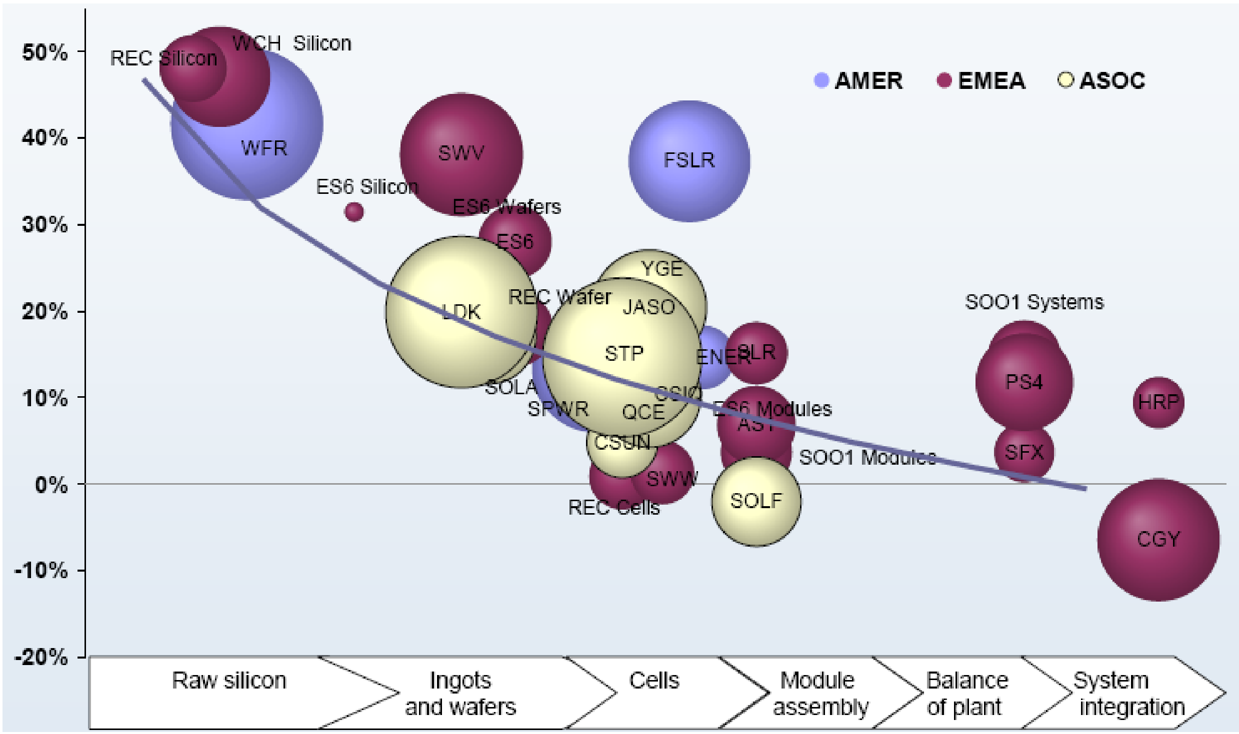
End-consumer costs for PV systems are at its lowest points historically, but actual module costs have been increasing since 2004. The prices of polysilicon and solar modules should be declining, not rising according to the experience curve. The unintended consequences of driving demand include a shortage of raw materials, resulting in higher feedstock and end-product prices. The current cost of solar modules has significantly deviated from the experience curve projected by Maycock (see Figure 10). The demand for solar modules and polysilicon is artificial, driven at least in part by generous government subsidies. Since subsidized consumer costs continue to decrease despite increasing unsubsidized costs, suppliers can raise prices without affecting their sales (see Figure 11).

Figure 10. Current PV module pricing versus experience curve projections



Henderson, R.M., Conkling, J., Roberts, S., 2007. Sunpower: focused on the future of solar power. Case study 07-042, MIT Sloan School of Management, July 25. Available: https://mitsloan.mit.edu/MSTIR/sustainability/SunPower/Documents/07-042-SunPower-Henderson.pdf

Figure 11. Earnings margins by position in the value chain (third quarter 2008)



New Energy Finance, 2009. Presentation, New Energy Finance Global Insight Overview, China, March 19

An argument can be made that the generous subsidies exacerbated or even created the current polysilicon shortage and high module prices. Total PV generation capacity nearly quadrupled since 2004, the year when the polysilicon prices began to rise. Polysilicon and other suppliers along the value chain benefitted from the windfall as polysilicon spot prices rose from $30/kg to $450/kg in 2004-2008. Earnings margins in excess of 45 percent were experienced by polysilicon producers during the third quarter of 2008. The profits earned by these private enterprises were subsidized by tax and ratepayers – yet another example of a tragedy of the commons.

The price of solar modules has deviated from Maycock's experience curve and prices have remained near constant since the cumulative capacity was 1,000 MW in 1999. Maycock's experience curve projected the cost of solar modules should have reach $1.30/W at a cumulative solar PV capacity of 10,000 MW, which was reached in 2008; module prices averaged $4.80/W in the first 4 months of 2009 (Henderson, 2007). Polysilicon prices, however, are projected to remain above $60/kg until 2015. Furthermore, there are no guarantees that raw material prices will ever retreat back to $30/kg.

The solar industry is predicted to grow an annual rate of 30 percent until 2020 (Bradford, 2006). If the industry is to keep up a 30 percent constant growth rate, an enormous amount of polysilicon and module production capacity will need to come online. PV capacity will increase 20 times its current size in the next 11 years at an estimated cost of over $1 trillion.

Demand can also be driven by non-financial policies. PG&E of California recently signed three power purchase agreements (PPAs) totaling 560 MW of solar energy (PG&E, 2007). There are few reasons why PG&E would enter into contracts that raises retail rates for its consumers but does not provide any real cost-reduction benefits. One reason is that California has a renewable portfolio standard that requires each utility company source 20 percent of its electricity from renewable resources by 2010 (Henderson, 2007). Renewable energy portfolios (RPS) or renewable energy standards (RES) are individual state policies that require certain amount of generation or generation capacity to come from renewable energy resources (see Table 7).

Table 7. Individual state renewable portfolio standards

State Renewable Portfolio Standards	**Renewable target**	**Year**
Arizona	15%	2025
California	20%	2010
Colorado	20%	2020
Connecticut	10%	2010
Delaware	10%	2019
Hawaii	20%	2020
Illinois	8%	2013
Iowa	105 MW	
Maine	20%	2000
Maryland	9.5 (2% from solar)	2022
Massachusetts	4% new	2009
Montana	15%	2015
Nevada	20%	2015
New Hampshire	25%	2025
New Jersey	20%	2020
New Mexico	20%	2020
New York	25%	2013
Oregon	25%	2025
Pennsylvania	18%	2020
Rode Island	16%	2020
Texas	5,880 MW	2015
Vermont	Equal to load growth	2005-2012
Washington	15%	2020
Washington D.C.	11%	2022
Wisconsin	10%	2015

Henderson, R.M., Conkling, J., Roberts, S., 2007. Sunpower: focused on the future of solar power. Case study 07-042, MIT Sloan School of Management, July 25. Available: https://mitsloan.mit.edu/MSTIR/sustainability/SunPower/Documents/07-042-SunPower-Henderson.pdf

Political mandates may not themselves demand government expenditures, but they can inflate the demand for renewable energy technologies. Aggressive RPS, however, are not sufficient for solar development. “Without a solar carve-out, any RES becomes a mandate for wind and biomass only,” since utility companies will pick the lowest cost generators available which generally does not include solar power (SEIA, 2008).

The ultimate problem of subsidies is that they are designed to provide the most support to those that need the most help. The policy is equivalent to a teacher giving a failing student the highest marks because s/he would otherwise fail out of school. The subsidy policies today are based on quantity; those that sell the most products receive the most subsidies. These do not necessarily encourage companies to develop a better product. Of the previous 16 innovations that led to significant decreases in manufacturing costs, only 6 were discovered by the solar industry. The rest were either discovered in research and development labs or adopted from other industries. The wire-saws used to slice silicon ingots into wafers, for example, were invented by the tire industry (Nemet, 2006). Innovative companies such as First Solar had earnings margins of 40 percent, doubling the margins of its competitors in Q3 2008. Subsidies should not allow companies that use outdated and otherwise uncompetitive technology to remain profitable. Research and development is inherently a risky venture, as the money invested may not necessarily yield positive returns. Support instead could be given in the form of research and development to innovative companies that have a track record of advancing photovoltaic technology. If the subsidy policies remain, there are public policy reasons why they should be revised to encourage risk taking and innovation, not profiteering.

The future of solar power

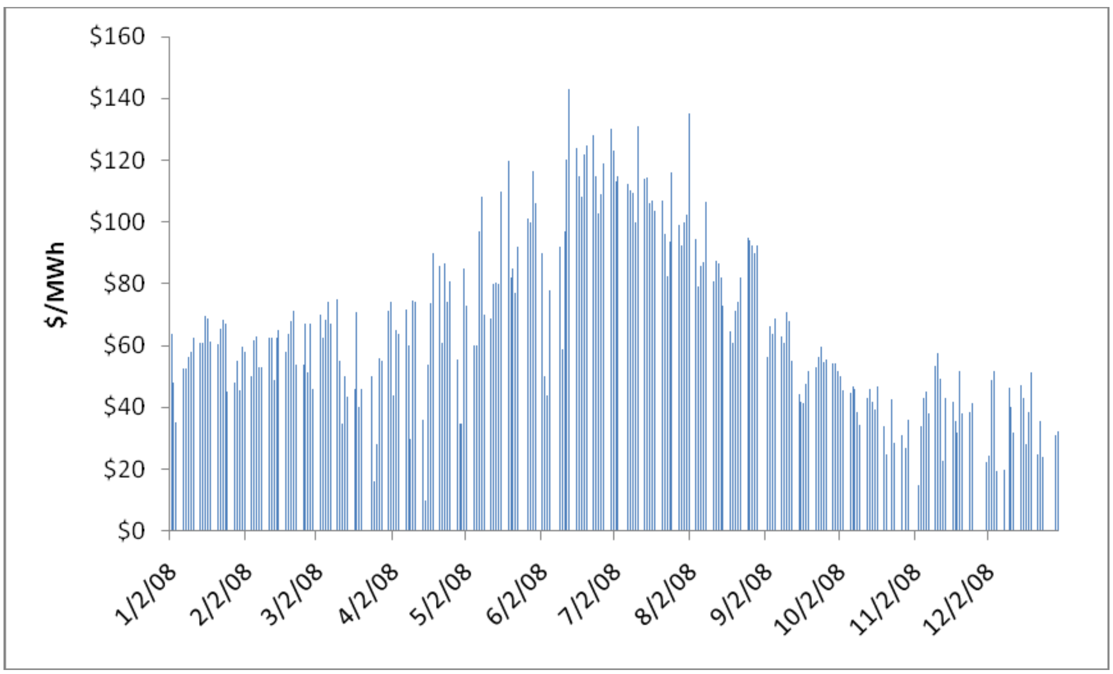
Solar industry analyst Travis Bradford, founder of the Promethus Institute, predicts that grid parity will be reached in markets with high quality solar resources within the next decade (Hard Assets Investor, 2008). Solar module costs have fallen significantly in the past decade and an increased supply of polysilicon will certainly help drive costs down. On the other hand, the solar industry has a history of optimistic predictions. The now defunct Chronar Corporation predicted in 1989 that it would be able to reduce the installed costs of a PV system to $2.50/W, thus lowering generation costs to 7-12¢/kWh by 1992 (Moore, 1989). Sunrgi of California predicts it will be able to supply electricity at a retail price of 5¢/kWh by late 2009, despite it not having commercially produced a single kilowatt-hour of electricity (Sunrgi, 2009). Solar generation technologies have been around for over 50 years and considerable investments were made in the technology in the 1970s, 1980s, and 1990s. Significant growth has only been achieved in the last few years, for which subsidies are largely responsible. The unsubsidized cost of solar generators today is still prohibitively expensive, with an installed cost of about $8,000/kW for residential and greater than $4,500/kW for most utility scale systems. This section analyzes whether solar energy will go the way of the semiconductor – achieve success beyond any expectations – or if it will follow the path of oil shale and synthetic fuels, and become a technology of failed potential.

Defining grid parity

The holy grail of solar power is the point of grid parity: when the cost per kWh of delivered solar electricity equals the cost of power from the grid. When grid parity occurs will the result be widespread deployment of solar power and a phasing out of conventional power? The question is difficult to answer since grid prices are dynamic and different power sources produce electricity under different conditions which produce base, intermediate, and peak power. Distributed PV generation systems will reach grid parity, as defended in this thesis, when the average peak wholesale price equals the LCOE of solar power. Utility-scale systems are usually located in remote locations so additional costs associated with transmission and distribution will delay grid parity. The following two sections delve deeper into explaining this position.

Electricity from natural gas generation usually costs more than electricity from coal generation. The two power plants also serve different functions which can allow a more expensive natural gas generation to have a higher value than coal. The value of kilowatt-hour available now is not necessarily worth the same as a kilowatt-hour available later. Like any other commodity, the value of electricity is determined by its level of supply and demand. For example, while the wholesale price of peak electricity in the Electric Reliability Council of Texas (ERCOT) market ranged from $4-10/MWh on April 15, 2008, the value of electricity on June 13, 2008 ranged from $140-143/MWh. The overall the market fluctuated between $4-143/MWh, with an average price of $63.41/MWh in 2008 (Figure 12) (EIA, 2009b).

Figure 12. ERCOT daily high traded wholesale electricity prices in 2008



EIA, 2009. Wholesale market data. Report, U.S. Energy Information Administration, April 22. Available: http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html.

The answer to why natural gas generated electricity can receive a price premium over coal generated electricity is explored from the point of view of an independent power producer (IPP) serving a simple wholesale market. This scenario assumes that the market is perfectly competitive and no single entity has the ability to influence the market price of electricity. It also assumes that all power generated is sold on the open market, not through PPAs. This hypothetical IPP has a portfolio containing a coal, simple cycle gas turbine, and PV solar power plants (see Table 8).

Table 8. Cost comparison of different generation technologies

Costs	**Coal**	**Simple cycle NG**	**Solar PV**
Capital ($/kW)	2,058	634	5,021
Fixed ($/kW-year)	27.53	10.53	11.68
Marginal (¢/kWh)	1.98	7.2	0

EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one

The cost structure of a power plant is made up of capital, fixed, and variable costs. The cost to build the power plant is represented by capital expenditures. Fixed costs are the necessary support needed to operate the power plant such as labor and insurance. Together, these costs are sunk and must be spent regardless of whether the plant generates 1 kilowatt-hour or 1 gigawatt-hour of electricity. The cost to produce every additional kilowatt-hour of electricity is its marginal cost.

Coal power plants are generally very large, with high capital expenditures, high fixed costs, low variable costs, and low fuel costs. Coal plants generally have high capacity factors, averaging nearly 74 percent in 2007 in the U.S. (EIA, 2009). The marginal cost per kilowatt-hour of electricity produced by a coal plant built today would be 1.98¢/kWh. Coal power plants can be responsive to operator input, but varying burn rates can lead to slag build up in the boilers. Coal power plants usually profit by selling large quantities of electricity at low profit margins.

A simple cycle gas turbine (SCGT) has distinct characteristics different from a coal plant, with SCGTs have low capital costs, low fixed costs, high variable costs, and high marginal costs. The operating characteristics of SCGTs make them very responsive to operator input. An operator can ramp up from a minimum to full production in as little as 15 minutes (Austin Energy, 2008). Because of its high variable cost, SCGTs are used sparingly, with an overall capacity factor of 11.4 percent in the U.S. in 2007 (EIA, 2009). A SCGT constructed today would have marginal costs of 7.2¢/kWh. The profit maximizing scheme therefore directs the IPP to wait until the market price of electricity exceeds the marginal cost of production from the SCGT. One feature of the wholesale market is that it features both real-time and forward trading. Trades can be executed immediately, hours-ahead, days-ahead, or weeks-ahead of the actual delivery time. Versatile dispatchable generation sources such as SCGTs or combined-cycle gas turbines (CCGT) have the option to enter into these types of trades to lock in prices and provide a set amount of generation for a future time.

Solar power plants have very high capital costs, low fixed costs, and zero variable and marginal costs. One feature that sets solar generation apart from coal or gas generation is that it is not dispatchable; the operator has no control over its electricity production. Solar power is inherently intermittent by nature. Its electrical output changes depending on the intensity of the sun. If the IPP builds a solar plant in Los Angeles, it expects that the plant will operate at peak production for approximately 2,000 hours per year (Solar Buzz, 2009). The IPP, however, does not know whether it will be producing power at noon on August 15, 2009. How, then, will the IPP behave? On the wholesale market, there is no minimum price at which the IPP will stop selling solar electricity since its marginal costs are $0.00/kWh. A solar generator in this model behaves more like a coal plant than a SCGT. Furthermore, a solar operator should not enter into forward delivery contracts because it cannot guarantee delivery at a certain date and time. Without this option, it cannot lock into high electricity prices and leaves itself at the mercy of the spot market.

Many operators of solar generators, however, have locked into long term PPAs, the details of which are discussed later on in the paper.

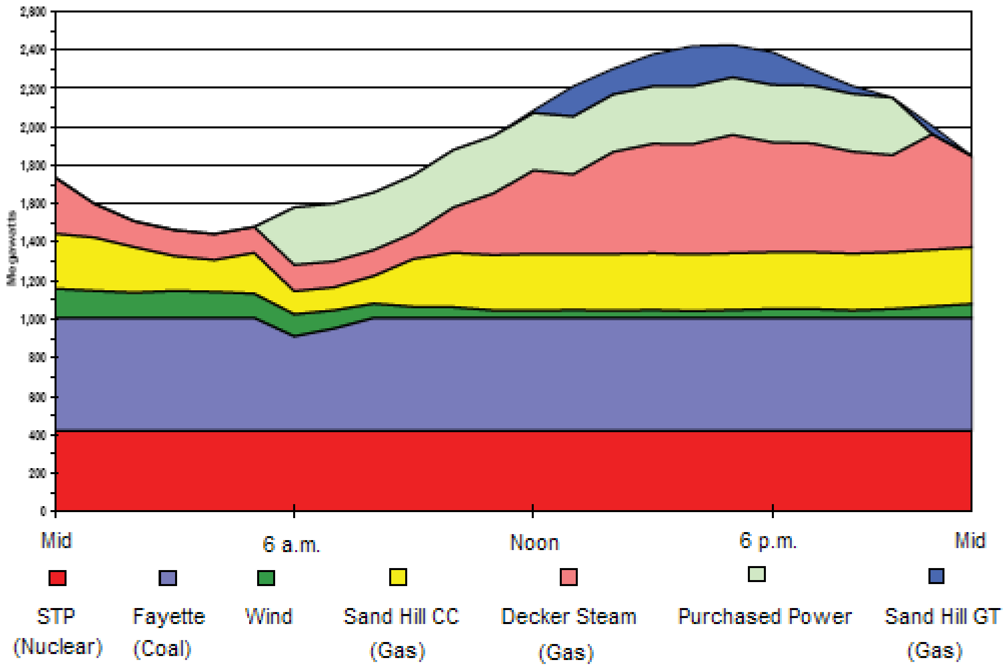
Cost is not the only consideration when evaluating a generation technology. The sensitivity of the electricity grid means that the timing of when electricity comes online is also very important. Certain fossil fuel generators such as SCGTs are versatile and can respond quickly to the demands of the grid, supplying more electricity when it is needed and cutting back when demand drops. The production of solar generators is hard to control as it and it depends on whether the sun is shining or not. Because of these traits, solar power does not fit in any of the traditional models. It is does not serve base-, intermediate-, nor peak load functions; it is in its own class.

Valuing solar power

In a completely free market, the value of a good or commodity is determined by the market. The arguments laid out in this section conclude that solar power is worth the spot price of electricity on the wholesale market at the point it is generated. The value of electricity depends on what kind of load it can serve or what kind of generation it can replace. Using the general rule of thumb, the value of electricity in ascending order is base-load, intermediate-load, and peak-load power. During periods where only base-load is required, ample generation supply is available. It makes sense that the lowest cost producers are used to provide that electricity. Peak power is normally priced higher than base-load power due to higher electricity demand, less available generation capacity, and higher production costs. Many solar analysts value solar power as peak power (Bradford, 2006; Hard Assets Investor, 2008). If solar generation technologies can replace traditional peak power generation sources solar power will have a high value. This section argues that solar power should not be valued as a peak generator.

Demand for electricity changes depending on the time of day and season of the year. The load can usually be balanced by base and intermediate load generators for the majority of the year. Peak load is not experienced often and generally occurs more frequently during the warmer summer months. For example, the load profile in August varies between 1,600 MW and 2,400 MW in Austin, TX (see Figure 13).

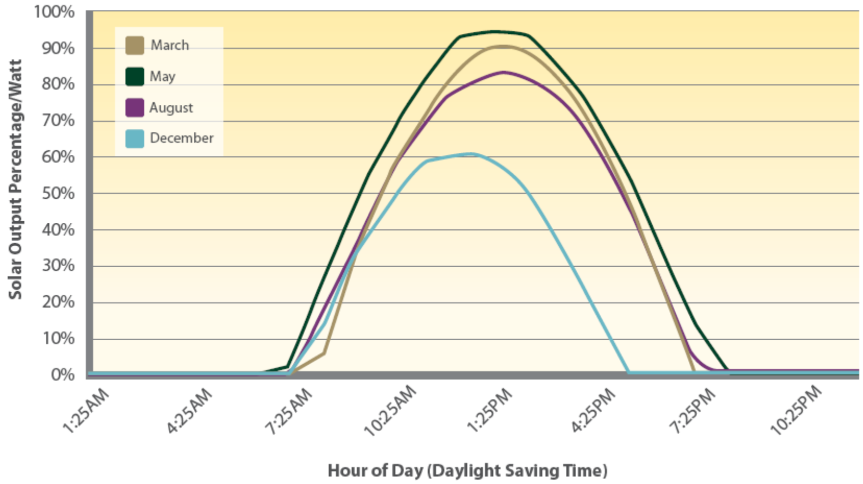
Figure 13. August Load Profile by Fuel Type, Austin, TX



Austin Energy, 2008. Resource guide: planning for Austin's future energy resources. Report, October.

If peak demand is arbitrarily defined as above 85 percent of the maximum annual load, the two sources of energy responsible for providing power over 2,000 MW demand are purchased power and a SCGT. Peak demand occurs roughly from noon until shortly before midnight, with the peak at sometime around 5:00 pm.

Figure 14. Monthly Output of Solar Power from Photovoltaics, Austin, TX.

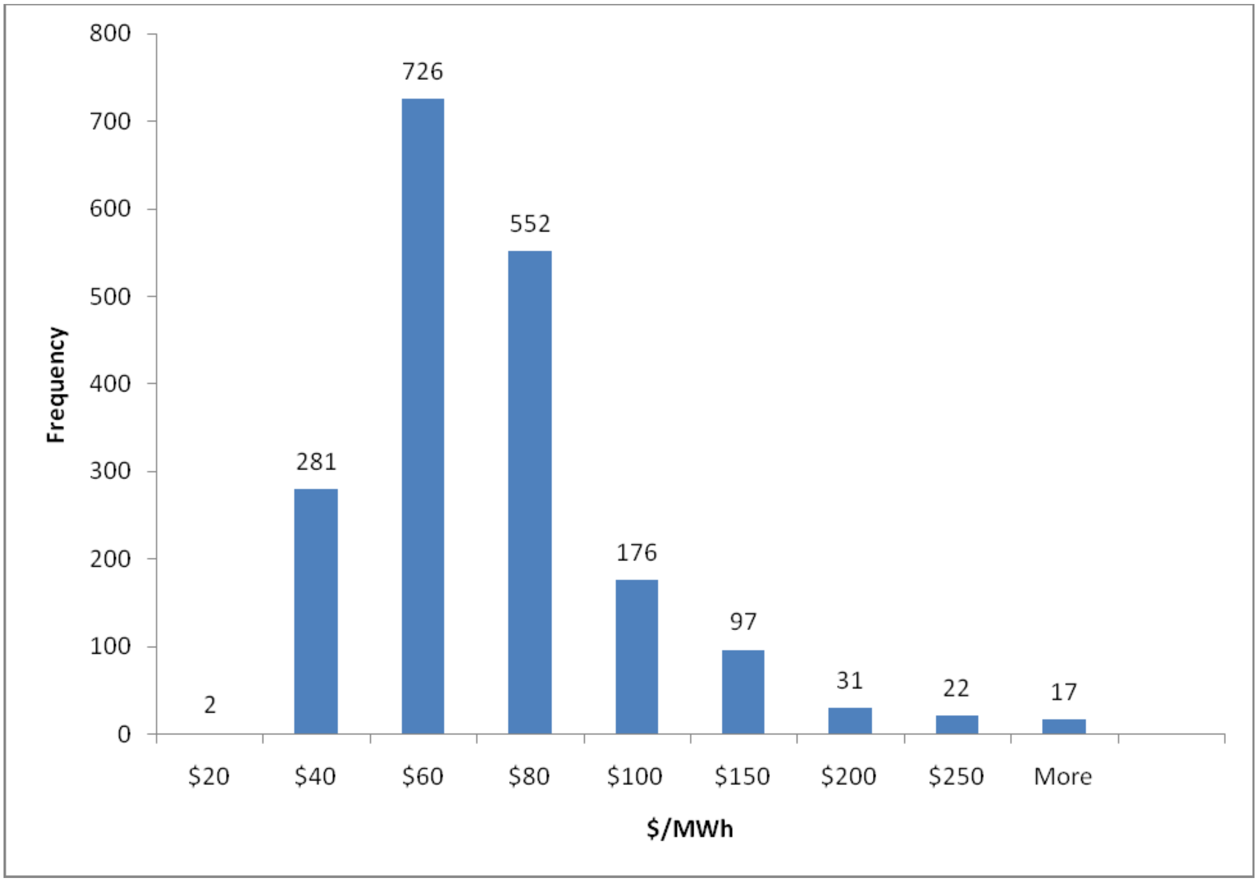


Austin Energy, 2008. Resource guide: planning for Austin's future energy resources. Report, October.

Compared to the electric load, the generation profile of a PV array located in Austin is does not follow the demand for electricity. Solar PV cells begin to produce electricity at sunrise, say at 7:30 AM just as demand begins to ramp up for the day. Peak production from the array in August comes at about 1:30 PM. By 5:00 PM when Austin Energy reaches its peak load, production from the array has already dropped to about 50 percent of its rated output. By 7:30 PM, the solar generator has stopped producing electricity while demand still exceeds 90 percent of peak load (see Figure 14). Solar generators operate when the sun is available, nearly every day of the year. Solar power can displace valuable peak generation in the summer. During the spring, fall, and winter, however, the power it produces has the value of intermediate or base load. Over the course of a year, the average price of electricity received by solar producers would probably be close to the average spot market price. SCGTs have similar capacity factors to solar generators. SCGTs can always receive premium pricing. These generators probably do not operate for 2.4 hours every day. The more probable scenario is that these generators do not run at all when electricity is cheap during the fall and spring, but operate for many hours during the summer to capitalize on higher electricity prices. Solar analysts should not compare the cost of solar power to the cost of peak power simply because it is the highest cost electricity. Peak generators provide a value that warrants its high production costs. Solar generators at the moment cannot provide that value. The ability to store energy, however, would give solar power the ability to control when its electricity is released onto the grid and command a premium price.

The average wholesale prices in 3 of the most expensive markets (the ERCOT in Texas, SP 15 in California, and NEPOOL in New England) was $29.12-$109.64 in the 2001-2008 period (EIA, 2009). Every so often there are anomalous periods when peak electricity prices reach into the $400-500/MWh range. Prices in this range however, are an uncommon occurrence (see Figure 15).

Figure 15. Distribution of SP 15 California whole market prices (2001-2009)



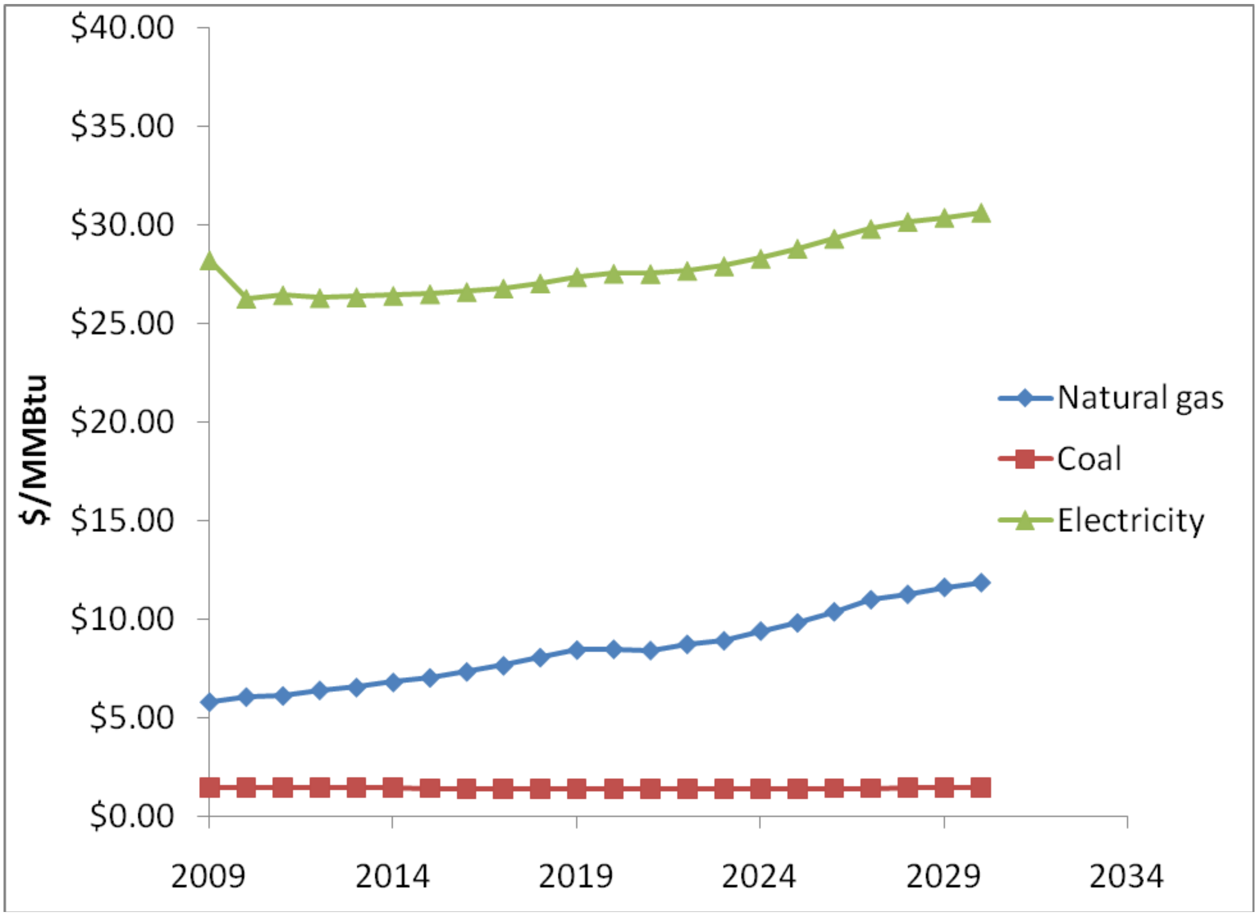
EIA, 2009. Wholesale market data. Report, U.S. Energy Information Administration, April 22. Available: http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html.

The SP 15 wholesale price exceeded $250/MWh 17 times in the 2001-2008 period. Wholesale market price exceeded $200/MWh 47 times in 2001 alone, with the remaining 28 times in the subsequent years. Unsubsidized solar generators have levelized costs of $234-584/MWh. In other words, based on cost alone solar generators would have been able to sell electricity profitably for 39 days in the last 8 years (2922 days). Electricity is only worth the market price at the moment it is produced; the ability to time electricity generation is the key to profitability for a high-cost generator.

Future energy prices

Increasing electricity prices can accelerate the path to grid parity for solar power. Fuel price spikes, volatility in commodity pricing, and environmental concerns have recently increased the cost of electricity from fossil fuel generators. Natural gas prices rose from $6.50/MMBtu to $10.50/MMBtu from January to August 2008 (EIA, 2008). A price forecast that reflects the current volatile environment of fuel prices was used to project future generation costs (Figure 16).

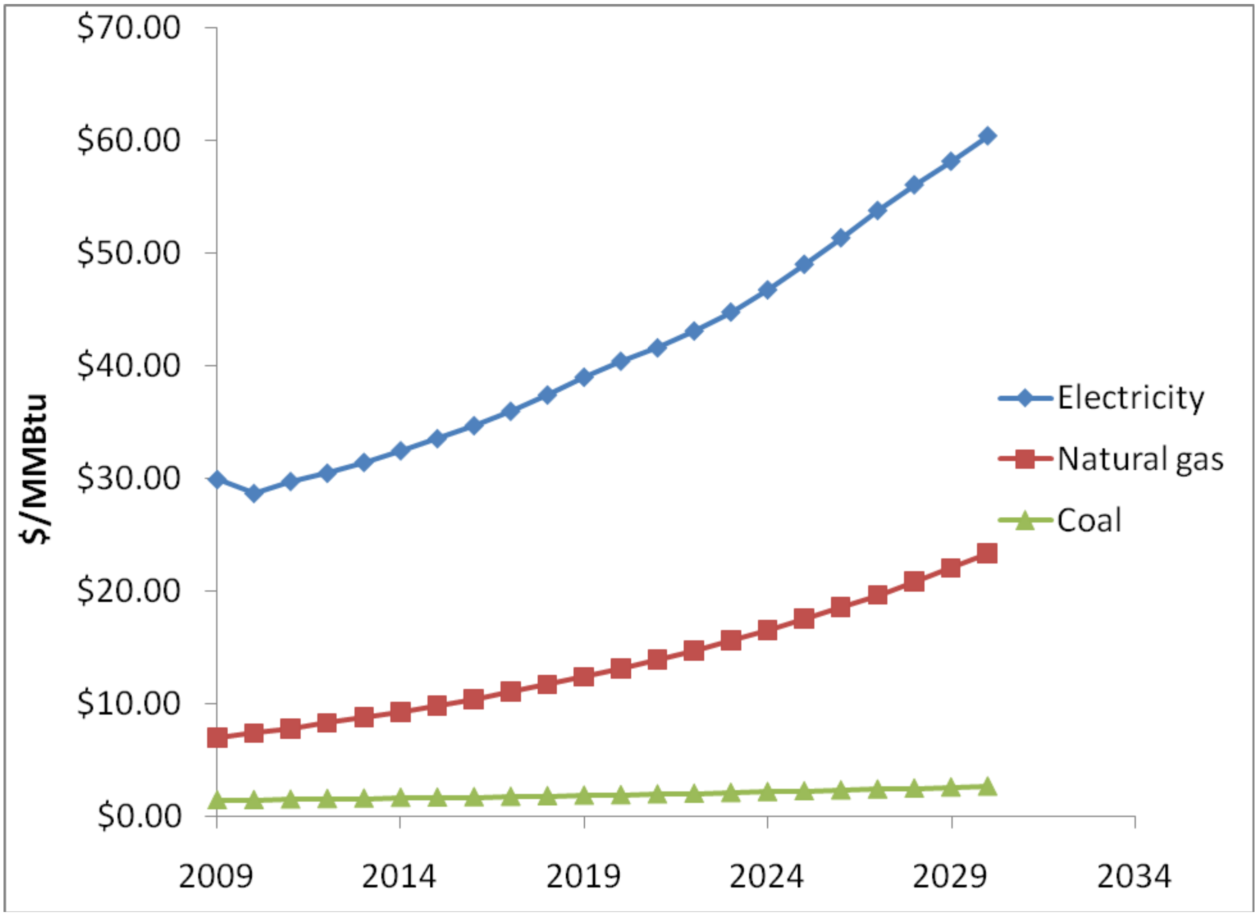
Figure 16. EIA energy price projections, 2007 dollars



EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one

In Figure 16 EIA price projections are expressed in constant 2007 dollars. The cost of coal is projected to stay constant for the next 20 years, most likely reflecting the large coal reserves in the U.S. Natural gas costs are projected to increase by a 2.83 percent average until 2030. All costs were then converted to nominal terms assuming a 3 percent annual inflation until 2030 (Figure 17).

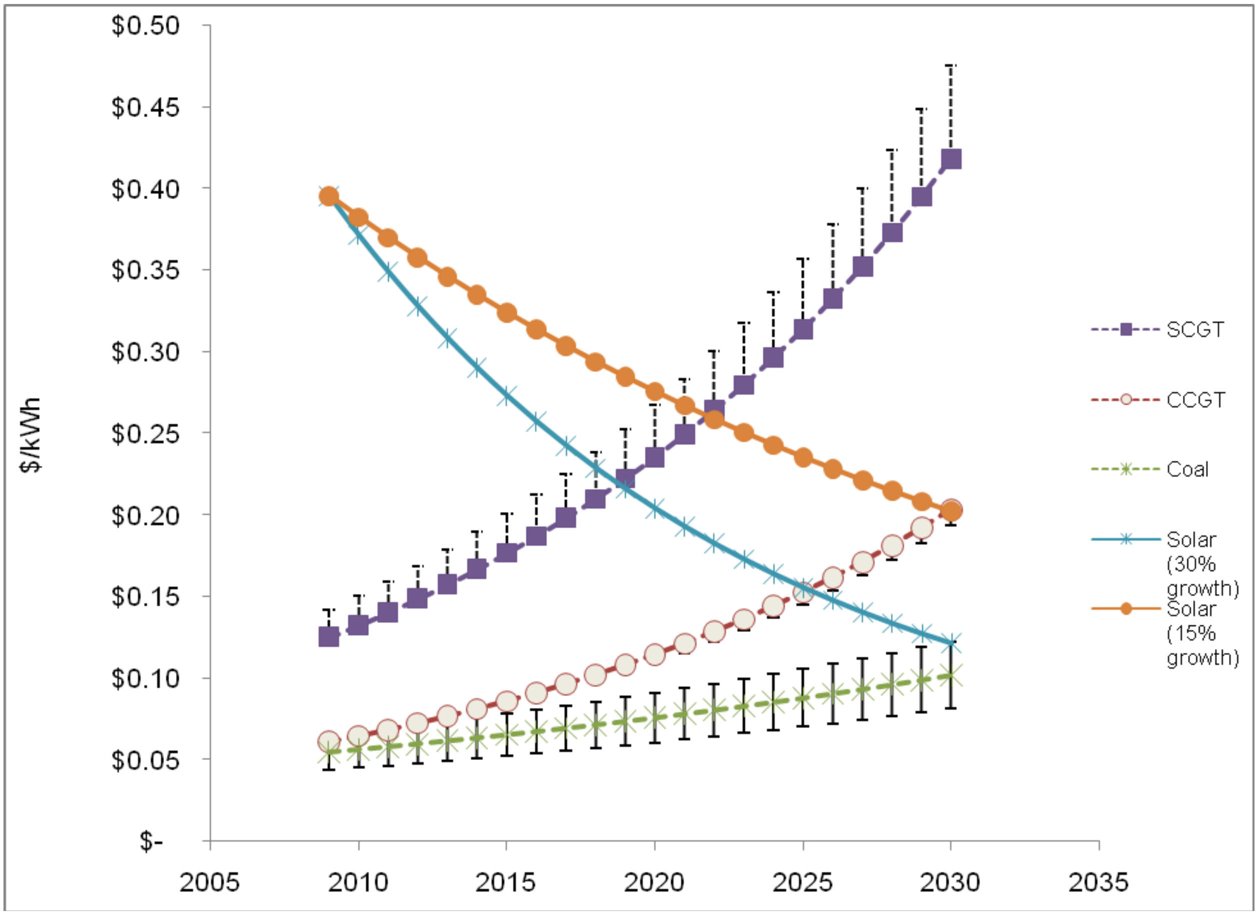
Figure 17. EIA energy price projections, nominal dollars.



EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one

The rate of inflation was chosen through a survey of the historical rate of inflation for the last 5, 10, 15, and 20 years. These rates were 3.20, 2.83, 2.70, ad 3.05 percent, respectively (Inflation Data, 2009). Electricity costs rise to $60.47/MMBtu or 20.6¢/kWh, while natural gas prices reach $23.37/MMBtu and coal increases to $2.69/MMBtu in 2030. The projection is that natural gas prices will increase by a nominal 5.92 percent per year until 2030. Electricity prices nearly increase by a nominal 3.5 percent per year until 2030. These cost estimates were intended to be aggressive, so as not to underestimate the cost of fossil fuel generation. Another consideration was the increasing cost of building power plants. High commodity costs such as steel and concrete, increasing environmental permitting costs, and construction delays from litigation have affected all power plants, especially coal (Schlissel, 2008). Duke Energy, for example, planned to build a two-unit coal fired plant in 2002 at a cost of $2 billion. Six years later, the cost nearly doubled with a new cost estimate of $1.8 billion for a single unit (Schlissel, 2008). The current high-cost construction environment was considered when modeling future generation cost projections (see Figure 18 and Table 9).

Figure 18. Electricity cost projections (2009 – 2030)



EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one;

Nemet, G.F., 2006. Beyond the learning curve: factors influencing the cost reduction in photovoltaics. Energy Policy 34(2006), 3218-3232.

Table 9. Marginal cost of electricity production in 2012 and 2030

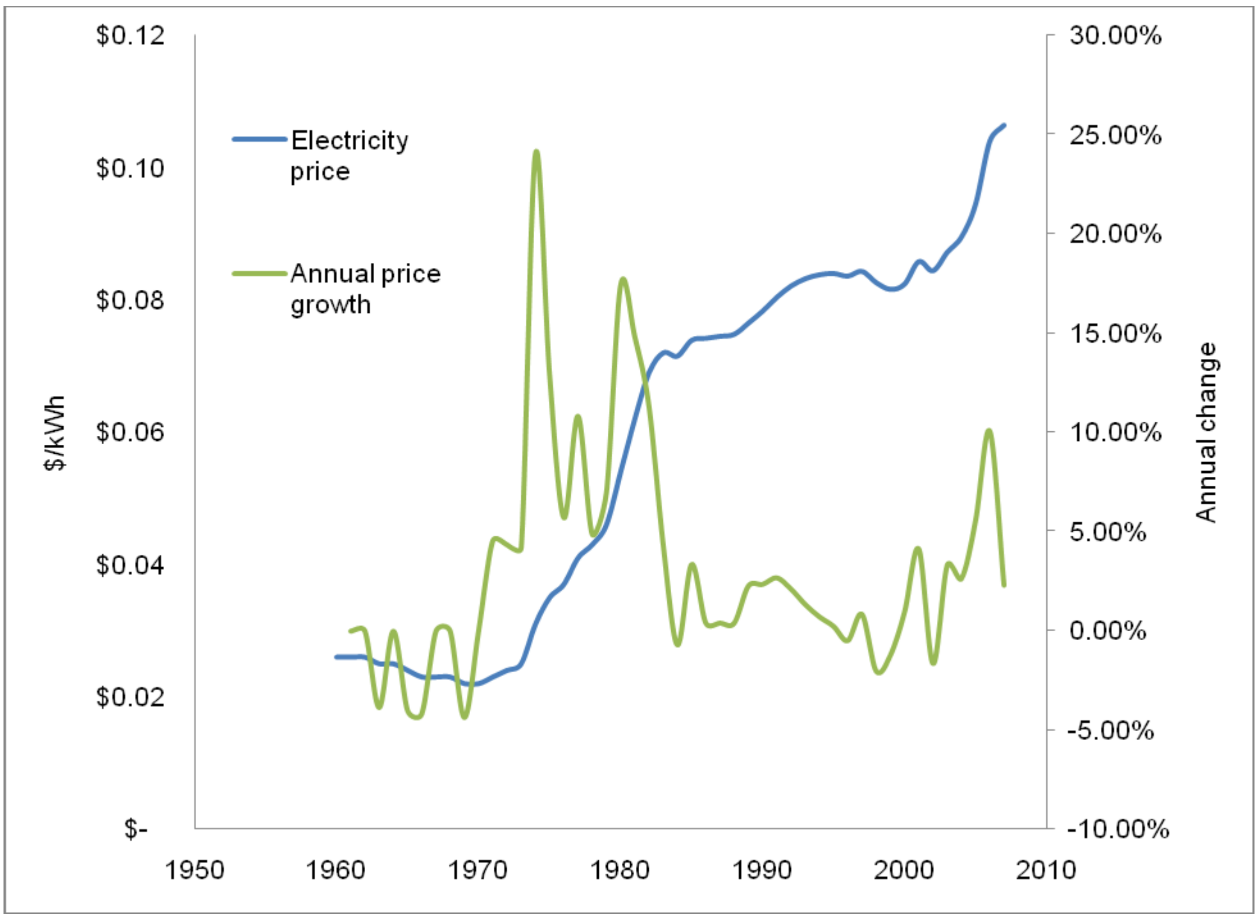
Generation source	**2012**	**2030**	**Difference**
Coal	2	3.4	70%
Combined-cycle gas turbine	5.8	22.3	284%
Simple cycle gas turbine	7.2	16.2	125%
Solar	0	0	0%

EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one

The future electricity cost projections were based power plants built today, using current capital costs as determined by the EIA (EIA, 2008). The cost of generation from natural gas fired plants will rise faster than generation from coal plants. The relatively low capacity factors of natural gas generators increases the dependence of average electricity rates on the cost of coal generation. SCGTs had an average capacity factor of 11.4 percent, CCGTs were 42 percent, and coal generators were 74 percent in 2007 (EIA, 2009). The EIA projection results in an electricity price of 20.6¢/kWh in 2030. The most recent costs projected by the EIA have been updated to reflect rising construction and permitting costs for all power plants, especially coal generators. Coal power plants are projected to produce electricity at a cost of 10.7¢/kWh. Electricity from a combined cycle gas turbine operating at a 42 percent capacity factor will cost 22.3¢/kWh. A simple cycle gas turbine will have generation costs of 44.4¢/kWh.

The solar generation cost projections were based only on PV generation. The Strategies Unlimited learning ratio of 0.17 was used. An initial module cost of $3.85/W was calculated to correct for the inflation from current polysilicon prices. Module costs were held at a constant 60 percent of total system costs. This projection also assumes that no further supply bottlenecks arise and that the manufacturing costs follow the experience curve. The crossover occurs in 2019 and 2025 for a SCGT and CCGT, respectively, assuming PV penetration grows by 30 percent annually. How does this compare to actual electricity prices? Some analysts have complained that price forecasts published by the EIA are too optimistic, resulting in unrealistically low retail electricity rates (Bradford, 2006). To avoid this criticism, a separate analysis of California electricity prices was performed using historical data. The forecasting strategy used was to pick a time period and inflate electricity prices by a constant rate for that period. One problem encountered was that historical data are extremely varied, thus it is difficult to choose a growth rate (see Figure 19 and Table 10).

Figure 19. Retail electricity prices (2008 dollars) in California (1960-2009)



EIA, 2008. Energy Perspectives. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/emeu/aer/ep/ep_frame.html

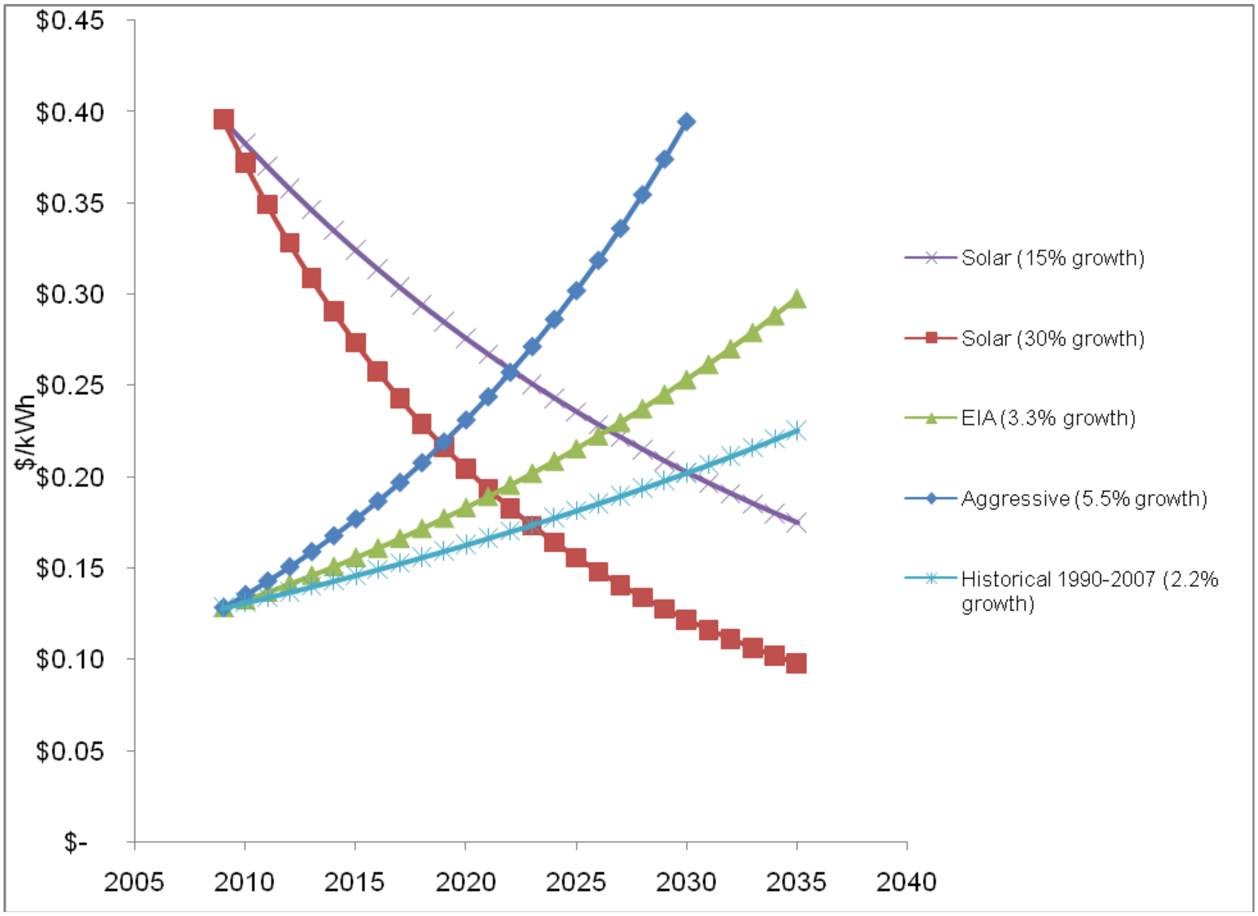
Table 10. Average annual retail price increase in various California markets

(%)	Residential	Commercial	Industrial	Total
2004-2007	5.5	3.5	2.5	4.1
2003-2007	4.3	0.7	1	2.1
1990-2007	2.2	1.8	1.9	2.2

EIA, 2009. Wholesale market data. Report, U.S. Energy Information Administration, April 22. Available: http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html

The decade from 1974-1983 was a period when electricity prices rapidly increased. The inflationary period ended and electricity prices remained relatively stable for almost the following 20 years. Electricity prices then rose by between 0.7 to 5.5 percent annually from 2003 to 2007. These data can be interpreted in several different ways, depending on the market. California electricity prices experienced periods of stability and periods of rapid price increases. The assumption of the future used in the modeling process discussed before assumes a constant growth rate until 2030 to balance the periods of rapid price increases with periods of flat growth. Three separate growth rates were used to project future electricity costs to compensate for the possibility of data manipulation: aggressively at 5.5 percent, the 3.3 percent projected by the EIA, and the historical 1990-2002 rate of 2.2 percent (see Figure 20).

Figure 20. Forecasts of California retail electricity rates and solar electricity costs



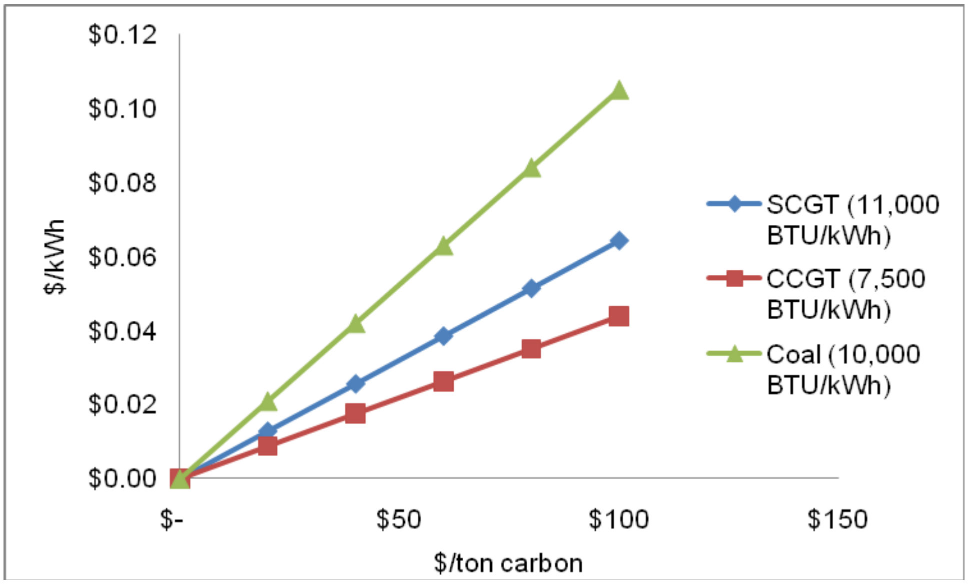
EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one;

EIA, 2009. Wholesale market data. Report, U.S. Energy Information Administration, April 22. Available: http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html

The addition of carbon pricing will make fossil fuel generation more expensive and the crossover will occur earlier. Figure 21 illustrates the effect of carbon pricing on generation costs. Every

$10/ton increase in carbon pricing results in coal costs increasing by 1.1¢/kWh, SCGT costs increase by 0.6¢/kWh, and CCGT costs increase by 0.4¢/kWh.

Figure 21. How carbon pricing schemes affects generation costs



Katzer, J., et al, 2007. The future of coal. Massachusetts Institute of Technology, Cambridge, Massachusetts[1]

The most optimistic projections forecast solar power to become cost competitive with grid-based electricity in 2019. PV capacity will be nearly 200,000 MW at that point with a total investment of almost $750 billion. A more moderate but still aggressive growth rate could result in a delay of the crossover to 2022-2031, depending on the rate of electricity price increases. The crossover point of solar electricity and grid-based electricity will most likely not bring on an energy revolution from fossil fuel to solar electricity. The sun is only available 40 percent of the time in

[1] Calculation based on coal energy content of 8400 BTU/lb, 48% carbon content; natural gas CO_2 content of 117lb/MMBtu

the sunniest locations; without the ability to store excess energy produced during the day for use later at night, solar penetration may have difficulty exceeding 15 percent.

The necessity of energy storage

Quads worth of energy were stored by nature in the physical form of fossil fuels. We humans harness the energy stored millions of years ago to power our homes and cars today and generate most of today's electricity. To generate more electricity, the burn rate is increased, and vice versa. Electricity, however, is like heat. It must be used at the time of generation, otherwise it is lost. The electricity grid is like a highway; the amount of electricity put onto the grid at point A will be delivered to point B. The grid is not a place where electricity can be stored or regulated. The result of delivering less electricity than needed can be a brownout. Delivering more electricity than can be used results in an overvoltage. Both of these occurrences can damage equipment, whether it is a light bulb or expensive manufacturing machinery. The enormity of the grid allows it to handle minor variations in voltage and frequency. Electrical devices also have designed tolerance to operate in a range of voltage and frequency without causing damage. The amount of electricity supplied must therefore match the amount of electricity used at any given moment within a given tolerance.

Electricity also differs from fossil fuels because, unlike coal or oil or gas, it cannot be stored in a barrel or container. The energy storage options available today convert electricity into another form such as compressed air or a battery charge, which can then be released and quickly converted back into electricity at a different time. One of the biggest barriers to harnessing the energy of the sun is its availability. The sun only shines 40 percent of the time in the sunniest areas of the world. A world fueled through solar energy requires energy storage options to capture excess electricity produced when the sun is available for use at night or on a cloudy day. There are only a handful of energy storage options available today – none of which are viable on a utility scale when paired up with solar generation.

Batteries are commonly used as a storage device PV arrays. The current technology can be applied on the scale of a home, but it is not advanced enough yet for utility scale applications. The most recent success demonstrated in battery storage technology was achieved by KEMA. It utilized two trailer sized battery stacks that delivered a total of 500 kilowatt-hours of electricity in a span of 15 minutes. The amount of electricity is not significant; it is about what an average American household uses in roughly 17 days (EIA, 2005). The costs of the experiment were also not revealed, but the cost of two trailer sized battery stacks would likely be prohibitively expensive for the amount of electricity it is capable of delivering. Its capability may be adequate for short-term load balancing, but the system would provide little value on a cloudy or rainy day, for example.

Storing energy in the form of heat used to create steam and drive a turbine is another possibility that is being explored. Spain-based Gemasolar is building a 17 MW utility-scale demonstration plant that will use molten salts as a storage medium (Martin, 2007). The Solar Tres project will be able to store enough energy to generate electricity for up to 15 hours. The disadvantage of this system is that the storage addition does not add versatility to the system; is still non-dispatchable. Heat is difficult to store as it eventually dissipates, making it a use-it or lose-it commodity. If the operators know that the fuel source will degrade whether or not the system generates electricity the decision will always be to generate electricity as long as the market price for electricity is higher than the marginal cost of production. Solar Tres will be a high capital cost, low marginal cost, and non-dispatchable generator putting it in the intermittent/base-load category. Assuming the project performs to specifications and is built on-budget, it is projected to have a high capacity factor of 74 percent and a LCOE of 26.7¢/kWh ($267/MWh). The technology has a long way to go before it can compete with other base load generators that produce electricity at a cost of less than 5.0¢/kWh.

One problem faced by solar energy is that grid reliability/load balancing issues will result once penetration exceeds 15 percent (Bradford, 2006). The non-dispatchable nature of solar energy means that reserve generation must be available to balance the electric load. No evidence was found suggesting that the industry was developing a roadmap to growing past the 15 percent penetration. The industry only appears to be focused on driving costs of solar electricity down.

The lack of a viable energy storage solution will become a serious barrier to a future solar revolution. The negative pricing phenomenon of the wind energy industry can be used as a case study. Adding energy storage would allow producers to store the unprofitable electricity to be sold on the market when electricity is more valuable, thereby increasing the value of wind power significantly. One reason it has not been added to augment wind energy systems is because it is not economically feasible.

Several energy storage technology used on a utility scale today have been available for decades. Compressed air energy storage and pumped storage are two examples, but both have their limitations. CAES requires a fossil fuel input and pumped storage requires certain geographical features. Many other technologies are in development, but far from routine commercial use. Hydrogen can be used as a storage medium, but the bulk of hydrogen produced today uses natural gas as its feedstock, not water. One important aspect to recognize is that those who stand to benefit most from energy storage are base load generators. Energy storage would give them the ability to store cheap electricity which it can resell for a higher price during peak periods. The probability that energy storage is not deployed on a wide-scale simply because it is not economically feasible today must be acknowledged. It is probably cheaper to install peaking units with high production costs instead.

The solar industry must recognize energy storage as a critical issue to continued development of the technology. It is careless for the industry to simply hope that a viable energy storage solution will be available by the time solar energy becomes cost competitive. Nuclear power was commercialized over 50 years ago. Society today still does not have a solution for nuclear waste. The industry needs to take an active role in this development to ensure that its future growth and viability are not limited by the lack of an energy storage option.

Conclusion

Solar power is a mature technology that is capable of generating and delivering electricity like any other generation source available today. The purpose of this thesis was not to debate the merits of solar PV, but rather the economics behind the technology.

One aspect ignored by this analysis goes beyond the economic benefits of having a solar energy system. People may derive a non-economic utility (happiness) from knowing that their electricity was generated by a renewable and pollution-free source. Austin Energy, for example offers a Green Choice program that allows its ratepayers a choice to purchase renewable energy. There is no difference in the quality of electricity delivered. The only difference observed by the ratepayer is in the bill: the Green Choice option is always priced higher than conventional electricity at the time it is offered. Subscribers today pay between $43.50 and $58.50/MWh more than ratepayers that have not subscribed to the program. Despite the additional increase in costs, the program is popular as 750 million kWh of AE's load is subscribed to the program. These Green Choice benefits are the same kind of utility people gain in driving a Lexus instead of a Toyota; drinking Poland Spring instead of tap water; or buying Advil instead of generic ibuprofen. The products all perform the same function. But to the people that cannot afford to subscribe to Green Choice, drive an Acura, drink Poland Spring, or buy Advil, the choice is straightforward and they are no worse off because of it.

Solar energy is a luxury product that still has a long road to grid parity. Rhone Resch, CEO of SEIA said in an interview on March 29, 2009 that the cost of solar panels decreased by 20-25 percent over the last 6 months. The cost decrease however, was not a result of technological improvements, but rather increasing government subsidies. Without government subsidies, the industry would not exist. The industry receives subsidies in excess of $200/MWh in Austin, TX; coal power as a comparison receives subsidies of $36.70/MWh, which include the externality costs currently paid by taxpayers. The RPS implemented by various states is not enough of a political mandate to install solar power. The industry requires a specific solar portion, otherwise solar energy is passed up for less expensive wind and biomass energy. The subsidy policies available today are not optimized to encourage actual research, development, and innovation, but represent payments for a quantity of product sold. The current policies allow otherwise unprofitable firms to remain competitive and only inflates the profits of the more efficient firms. Subsidy policies should be modified to promote innovation instead of profiteering.

The current cost of solar power is 24.0 to 58.4¢/kWh, compared to the average utility rate of 12.8¢/kWh in California. If the experience curve is to be believed, the most optimistic projections have distributed solar generation becoming cost competitive in the California market in 2020 after more than $1.1 trillion of investments. Grid parity will probably not signify a changing of the guard from fossil fuel to solar generation. The sun is only available 40 percent of the time in the sunniest locations; without the ability to store excess energy produced during the day for use later at night, solar penetration is not likely to exceed 15 percent. The lack of viable storage options for the wind industry has led it to selling its electricity for negative prices during certain periods. With storage, solar energy can ignite an energy revolution once it does become cost competitive. The author was unable to find evidence that the solar industry was applying the lessons learned by the wind industry and is not actively developing a storage solution. Several decades ago, nuclear energy became commercially viable; we as a society still have not developed a method to safely dispose of those spent fuel rods from the first reactors. The possibility that solar power will always remain as the energy source of the future must be considered, especially if this energy storage hurdle cannot be overcome.

The ability to harness the sun as an unlimited and clean resource is certainly a romantic ideal, but has not demonstrated itself to be a viable option yet. The energy problems that we experience today and anticipate for tomorrow has can be mitigated on several fronts. Using energy more efficiently can be an effective way to reduce energy use in the face of higher prices. Recognize that renewable energy can be found almost anywhere. A handful of examples include mining heat from deep beneath the Earth’s surface, thermophotovoltaic cells that utilize infrared (heat) waves to generate electricity, or small-scale turbines that can be powered by river currents. Solar energy is not the only solution. Developing a technology to economically harness solar energy would certainly alleviate many of the problems associated with energy today, but there are also many more resources available with just as much potential to create an energy revolution.

Appendix A

Name	Type	Size (MW)	Year completed	Capital cost ($/kW)	Capacity factor (%)	Fixed costs ($/kW-year)	Variable costs (¢/kWh)	Reference
Conergy SinAn	Silicon PV	19.6	2008	5,969	16	11.68	0	Conergy, 2008. Conergy completes Asia's largest Solar Power Plant in South Korea and gets commissioned with the turnkey construction of additional 4.35 MW. Press release, August 13. Available: http://ep.its.ac.id/wp-content/conergy-24-mw-sinan.pdf
Sky Power	Thin film	19	N/A	4,189	10.9	11.68	0	Project Finance Magazine, 2008. First light: the sunny north. Article, December 19.
Rote Jahne	Thin film	6	2007	4,667	10.9	11.68	0	Juvi solar GmbH, 2008. Sunny outlook in Saxony. Press release, April 5.
Solar Tres	Power tower w/storage, 15% gas	17	N/A	13,000	74	56.78	0	Martin, J., 2007. Solar Tres. Presentation, NREL CSP Technology Workshop, Denver, Colorado, March 7. Available: http://www.nrel.gov/csp/troughnet/pdfs/2007/martin_solar_tres.pdf
SolFocus	CPV	10	2008	10,000	40	11.68	0	Semiconductor Today, 2008. SolFocus installs first solar array for 3MW Spanish CPV project. Article, February 5, 2008. Available: http://www.semiconductor-today.com/news_items/2008/FEB/SOLFOCUS_050208.htm
Austin home	PV	0.036	2009	8,000	20	11.68	0	Austin Energy, 2008. Resource guide: planning for Austin's future energy resources. Report, October.
Andasol	CSP (w/storage)	49.9	2008	7,600	40	11.68	0	Biello, D., 2009. How to use solar energy at night. Article, Scientific American, February 17. Available: https://www.sciam.com/article.cfm?id=how-to-use-solar-energy-at-night
Nevada SolarOne	CSP (w/storage, 2% gas)	64	2007	4,150	23.5	56.78	0	Acciona, 2008. ACCIONA opens "Nevada Solar One", the biggest solar thermal electric plant built in the world in the last 17 years. Press release, February 23. Available: http://www.acciona.com/press-/news/acciona-opens-%E2%80%9Cnevada-solar-one%E2%80%9D-the-biggest-solar-thermal-electric-plant-built-in-the-world-in-the-last-17-years
EIA Estimate	SCGT	100	N/A	421	10	10.53	0.317	EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one
EIA Estimate	CCGT	100	N/A	621	85	12.48	0.203	EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one
EIA Estimate	Coal	800	N/A	2,058	74	27.53	0.459	EIA, 2009. Electric power industry: 2007 year in review. Report, U.S. Energy Information Administration. Available: http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html#one
Duke Energy (2002 estimate)	Coal	1600	N/A	1,250	N/A	N/A	N/A	Schlissel, D., Johnston, L., Kallay, J., James, C., Sommer, A., Biewald, B., Hausman, E., Smith, A., 2008. Don't get burned: the risks of investing in new coal-fired generating facilities. Report, Synapse Energy Economics, Inc., New York.
Duke Energy (2008 estimate)	Coal	800	N/A	2,250	N/A	N/A	N/A	Schlissel, D., Johnston, L., Kallay, J., James, C., Sommer, A., Biewald, B., Hausman, E., Smith, A., 2008. Don't get burned: the risks of investing in new coal-fired generating facilities. Report, Synapse Energy Economics, Inc., New York.

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Vita

Alexander T. Wong attended the University of Wisconsin-Madison. He graduated with a Bachelor of Science in December 2005. In January 2007, Mr. Wong entered the Graduate School at The University of Texas at Austin. His professional interests are energy project development and government regulatory affairs related to the energy industry. In his spare time, Mr. Wong enjoys the outdoors and traveling. So far, he has slept in a train station, bus station, or airport in every country he has visited.

Permanent Address:

240 118th Ave SE, #13
Bellevue, WA 98005

This thesis was typed by the author.