PAYBACK AND CURRENCIES OF ENERGY, CARBON DIOXIDE AND MONEY FOR A 60 KW PHOTOVOLTAIC ARRAY

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ABSTRACT

We evaluated the time it will take for a PV array installed in NE Ohio to pay back the energy, carbon dioxide and money initially invested. Carbon dioxide expenditures are recovered in 3.7 years and energy in 7.3 years. The financial investment is not recovered during the useful life of the panels unless the external environmental and health costs of displaced fossil fuel energy are incorporated in the calculations. Differences in payback times for different currencies are indicative of a disconnect between environmental and economic values.

1. INTRODUCTION

The direct conversion of sunlight into electricity via photovoltaic (PV) modules is widely considered a potential solution to environmental problems such as acid rain and global warming caused by conventional electricity generation. But while solar energy is renewable, there are significant investments of energy made during the PV manufacturing process. Currently this energy is derived largely from non-renewable fossil fuels, and PV production is therefore associated with the production of pollutants. A PV installation can only be considered "green" if the net environmental benefits that accrue over its useful lifespan of energy production and associated pollution displacement exceed the net environmental costs invested in manufacturing and installation.

"Payback time," the time it takes for a technology to generate earnings that are equal to its full production, installation and operating cost, provides a useful metric for assessing the economic and environmental value of a given installation. For grid-connected PVs, financial payback times are determined by the cost of the panels, by the value of electricity (both purchased and sold) where they are installed and by the quantity of the solar resources that characterize the particular installation site. Environmental payback is dependent on the impacts of the energy used to manufacture the panels and on the impacts of the grid energy that is displaced when the panels are in operation. Previous studies of these environmental costs have typically focused on aggregate effects of national and regional mixes of energy (e.g., Kato, Murata et al. 1998; Alsema 2000). We argue that, for a given installation, payback times are highly dependent on both the particular local mix of energy resources used to manufacture the solar panels and the mix of energy resources that characterize the electrical grid in which the panels are installed. Furthermore, for grid-connected PV systems installed on buildings, payback also depends on the relationship between patterns of electricity use within the building and the contractual relationships with the local utility. In order to explore this site-specificity, we conducted separate payback analyses using currencies of energy, carbon dioxide (CO_2), dollars and externalized costs to consider the environmental and financial value of an array installed in Oberlin, Ohio.

2. METHODS

2.1 System Description

Our analysis centers on a 60 kilowatt (kW) monocrystalline silicon (mc-Si) PV array. The 4,800 sq-ft (446 sq-m) installation is roof-mounted on the Adam Joseph Lewis Center (AJLC) for Environmental Studies at Oberlin College in Oberlin, Ohio. It consists of 690 85 W modules manufactured by BP-Solar (model #585) arranged in three 15 kW sub-arrays. The roof is elongated on an east-west axis and faces directly south but is curved so that the first of the ten rows is at an angle of 20° below horizontal and the last is at an angle of 9° North. The mounting system is constructed of aluminum and stainless steel. Each sub-array feeds into a 15 kW inverter (Xantrex Technology), each inverter is connected to an isolation transformer (Square-D), and power generated is directed to a main distribution panel. The Oberlin array began operation on Nov. 14th, 2000 at a total cost of $386,000 (approx. $6.60/Watt), which includes design fees, modules and all installation costs. The system is grid-connected; when PV production exceeds building consumption, electricity is exported.

A data acquisition system (DAS) was installed in Jan., 2001 to monitor performance of the building and the PV system. The DAS is comprised of watt-hour transducers (Continental Control Systems), dataloggers (Campbell Scientific) and a PC server that monitor and store data on electricity production by the PV system and electricity consumption of the major end-uses within the building. For the period between the PV start date (Nov. 14th, 2000) and the installation of the DAS (Jan., 2001), data from a utility-owned meter was used to monitor PV performance.

2.2 Calculating costs, revenues and payback times

Regardless of the particular currency under consideration, the same general cost-benefit approach can be used to assess the net value of a photovoltaic installation. Costs include the initial expenditures of money, energy or pollution involved in manufacture and installation, and any further expenditures needed to maintain and ultimately dispose of the equipment. Revenues, on the other hand, accrue over the entire useful lifetime of the system in the form of electrical energy generated, pollution averted (as a result of not using more harmful energy generation technologies), and money earned or saved. The net value of a PV installation can be independently assessed for any currency. Payback time is simply the point in time at which accrued benefits exceed accrued costs.

Although the general approach for calculating payback is similar, the particular costs and revenues are distinct for each currency. The degree of precision possible in analysis also differs among currencies. For instance, determining simple monetary payback time is a relatively simple and precise exercise. In contrast, determining energetic and environmental payback is complicated because key information on the manufacturing process and on environmental costs is not readily available. Our analysis is necessarily limited by the assumptions embedded in the previous studies that we use to estimate environmental costs and benefits. Furthermore, estimation requires that somewhat arbitrary decisions be made about which costs and benefits to include and which to exclude (i.e. system boundaries). We aimed to clearly identify assumptions in our estimation. When faced with a choice, we have biased our assessment so as to assume the higher cost.

3. ENERGY PAYBACK

3.1 Energy expenditures

A complete analysis of the energetic costs of the Oberlin installation would include all energy used in the manufacturing, transportation, installation and maintenance of all components of the system. However, our analysis indicates that energetic costs of manufacturing the modules and other hardware dominate the total energy budget. For this reason, our evaluation of the Oberlin installation considers only these costs and we have excluded the following energetic expenditures from our analysis: 1) energy used to construct the facilities in which the PV modules and parts are manufactured, 2) energy used in transportation, 3) indirect energy used by employees involved in producing, installing and marketing the PV system, 4) energy used to install the array on the roof of the building, and 5) energy used to maintain the system and to decommission it when its useful life is exhausted. For those processes that involved the direct use of fossil fuels (e.g. aluminum smelting), we estimate values in electrical equivalents by expressing energy in kilowatt-hours (kWh) and multiplying by 35% to account for the conversion from primary to secondary energy units.

Producing the modules represents a significant percentage of the energetic expenditures associated with the Oberlin installation. Knapp and Jester (2001) provide the only empirical accounting in the literature of energy consumed in the manufacture of mc-Si PV modules. They estimate a ratio of 5,589 kWh of embodied energy per 1 kW of rated output of the modules produced. With a total rated output of 58.65 kW, we therefore assume an embodied energetic cost for Oberlin’s modules of 328 MWh.

In addition to the PV modules themselves, a significant amount of energy was used to manufacture the “balance of system” (BOS) components including the roof mounting hardware, inverters, transformers and cabling that are part of the Oberlin system. Based on engineering diagrams and empirical measurement, we estimate that the mounting system contains 475 kg of primary (virgin) aluminum and 313 kg of stainless steel. When converted to secondary energy units, the embodied energies per kilogram of primary aluminum and steel used are 67 kWh kg^{-1} and 9 kWh kg^{-1} respectively (Demkin and AIA 1996). Thus, aluminum contributes 32 MWh and steel contributes 3 MWh to the energetic cost of the array. No published studies have evaluated the embodied energies of inverters, transformers and cabling. Rather than omit a potentially important source of embodied energy, we adopt the estimate of others in assuming a 0.28 kWh per rated watt of module power for the combined energy embodied in this equipment (Alsema and Nieuwlaar 2000). We estimate a total BOS energy investment of 40.3 MWh. Together with the PV modules themselves, this amounts to a total energetic cost of the Oberlin installation of 369 MWh, or 6.28 kWh per rated watt.

3.2 Energy revenues

Based on our DAS and the independent meters installed by Oberlin Municipal Light and Power, we can determine PV electricity production to date with a high degree of certainty. We know, for instance, that in 2003, the array produced a total of 51.4 MWh of electricity. Determination of payback necessitates that we estimate future production and this, of course, is less certain. To do this we needed to estimate both future weather conditions and rates of panel power degradation. Although greenhouse gas related climate change in NE Ohio will likely alter patterns of temperature and insolation (Kling et al. 2003), we assume that conditions in the recent past are still the best available indicator of the future. A careful comparison of local solar insolation data recorded between 1961and 1990 with data obtained by the DAS indicates that average monthly insolation during the first 35 months of PV operation is typical of prior long-term patterns.

Predicting electrical output of the PV array per unit solar radiation into the future is complicated by the fact that modules have a finite lifespan. Output decreases over time as a result of both gradual and catastrophic failure of materials. Many studies of long-term performance of silicon PVs exist (e.g., Hishikawa, Morita et al. 2002; Reis, Coleman et al. 2002). While silicon is very well understood from a materials science perspective, constant improvements by the PV industry make it difficult to use previous studies to predict long-term performance of the Oberlin array. We chose a 1% per year decrease in output, which is slightly greater than the greatest performance degradation rate quoted in studies cited above. This degradation rate was applied to all energy projections.

BP-Solar guarantees 25 years of power output from Oberlin's modules. For the purposes of our analysis, we assumed lifetime energy production under two scenarios by estimating production for 25- and 40-year lifetimes. We also used these two scenarios to estimate CO_2 and monetary payback. Based on the performance of the Oberlin installation so far and a 1% yr^{-1} degradation rate, we estimate a total production of 1,194 MWh for a 25-yr and 1,753 MWh for a 40-yr lifetime. This corresponds with an energy payback time of 7.3 years.

4. CARBON DIOXIDE

4.1 CO_2 expenditures

CO_2 emissions are closely associated with energy use. We assumed that the majority of energy expenditures were associated with the manufacture of the modules and BOS components, and we therefore ignore CO_2 expenditures emitted in other portions of the PV lifecycle. Also, because electricity is the dominant form of energy used in manufacturing solar modules, our analysis assumes that CO_2 emissions from this component of the Oberlin installation can be entirely attributed to electricity generation (Alsema 2000; Alsema and Nieuwlaar 2000; Knapp and Jester 2001).

CO_2 payback is dependent on the quality as well as the quantity of energy used in manufacturing the array. Specifically, payback depends on the carbon intensities (CO_2 released per kWh generated) of the fuel mix used in the location where each component of the array is manufactured and on the fuel mix used to generate the electricity sold by the local utility in which the PV system is installed. CO_2 payback occurs most rapidly for PV systems manufactured in locations using low carbon intensity fuels and installed in locations dominated by electricity generated with high carbon intensity fuels.

Although carbon intensity for a given fuel source varies as a function of the particular generation technology employed, average intensities can be calculated. In the U.S., carbon intensities are 2.12 lbs CO_2 kWh^{-1} for coal, 1.92 for oil, 1.31 for gas, 0.02 for nuclear and 0 for hydro fuels (Energy and Agency 2000). The carbon intensity of a nation and of each local electrical utility varies greatly depending on the fuel mix. For instance, the average carbon intensity is 1.11 lbs kWh^{-1} for Japan, 1.21 for Spain, 1.45 for the U.S. and 2.16 for Oberlin, Ohio (in calculating these numbers we assumed the same carbon intensity of the average power plants in the U.S and assumed an additional 7.64% line loss between generation facilities and PV manufacturing facilities). The high carbon intensity value for Oberlin is due to the dominance of coal as an energy source in North East Ohio and is also a function of complications associated with the emerging market for "green" energy (electricity produced in ways that are considered less harmful to the environment). Although Oberlin Municipal Light and Power obtains 17% of its total energy from a mixture of relatively low carbon intensity hydropower and landfill gas, the "green attributes" of this power are sold to Green Mountain Power, a green energy broker that markets them elsewhere. In calculating the carbon intensity for Oberlin, we therefore eliminated the percentage of these energy sources from the total mix.

Like most contemporary products, Oberlin's PV components are global in origin. Although challenging to trace, to the best of our knowledge the wafers were made in Japan, the cells were processed in Spain and the modules were assembled either in Spain or in California (Wohlgemuth 2003). For the purposes of this analysis we have assumed the modules were made in Spain because Spain's electricity supply relies more heavily on carbon intense fuels such as coal and oil than does California's (World Bank 2002; Energy 2002). The bulk of energy in manufacturing PV modules is consumed in the silicon purification and crystal growth processes (Alsema 2000; Alsema and Nieuwlaar 2000; Knapp and Jester 2001). We estimate that wafer production in Japan used 281 MWh of electrical energy, and that cell and module production in Spain used 107 and 87 MWh, respectively.

We used national fuel mixes in the countries involved to convert energy consumption to CO_2 emissions. Wafer production was responsible for 225,700 lbs of CO_2, cell production 92,500 lbs, module assembly 75,500 lbs and BOS components 16,100 lbs of CO_2. For the aluminum and stainless mounting equipment, instead of using electrical conversion factors, we used carbon intensity values for primary fuels involved in smelting and manufacturing (Department of the Environment 2002) and determined that aluminum resulted in an additional 300 lbs of CO_2, cabling 8,400 lbs, and steel 420 lbs. In total, the Oberlin array resulted in emissions of 409,800 lbs of CO_2.

4.2 CO_2 revenues

We assume that all energy produced by the Oberlin PV array, whether used within the building or exported onto the grid, directly displaces CO_2 that would otherwise be emitted by energy available through Oberlin Municipal Light and Power. With PV production of 51.4 MWh and a carbon intensity value of 2.16 lbs CO_2 kWh^{-1} for local utility power, this amounts to revenues of 111,200 lbs of CO_2 for 2003. In predicting CO_2 revenues into the future, we adopt the same assumptions as we did for energy regarding panel degradation and useful lifespan. Changes that may occur in energy intensity of the fuel mix used in Oberlin, Ohio represent a major uncertainty in predicting CO_2 payback times. As we write, Oberlin College is in negotiations with the local utility to purchase all of the available green attributes that our local utility is currently selling to Green Mountain Power. The utility itself is also negotiating to purchase electricity from a wind turbine. Either action would reduce the carbon intensity of the local fuel mix and thereby effectively increase the CO_2 payback time for the Oberlin installation. Furthermore, if policies in the United States change in response to increasing global concern about greenhouse gases, adoption of economic measures such as a carbon tax could also drive the local market towards lower carbon intensity electricity. However, since none of these actions is certain we have based our payback calculations on the assumption that carbon intensity in Oberlin will remain at current levels throughout the useful lifespan of the PV system. We therefore estimate total CO_2 revenues of 2,582,000 and 3,791,000 lbs based on 25- and 40-yr lifespans, respectively, and a payback time of 3.7 years.

5. MONEY

5.1 Scenarios for calculating payback

Monetary payback of the Oberlin array can be calculated in a number of ways and we consider three distinct scenarios: 1) *Simple payback* assumes only the direct costs and revenues of the system as it was installed and as it is credited by the utility; 2) *payback with green attributes* assumes that Oberlin College either sells or internally credits the financial value of the green attributes associated with PV production; 3) *payback with externalities* adjusts payback based on the externalized environmental and health costs not incorporated into the current price of fossil-fuel based energy.

5.2 Simple payback

The direct financial revenues of a PV installation are a function of solar resources and of the contractual agreement with the local utility for purchasing and selling power. Ohio has "net metering" legislation, which means that our local utility is obliged to credit excess power produced by the Oberlin installation at retail prices. Oberlin College pays a \$15/month fixed customer charge and \$0.05 kWh^{-1} for electricity that travels from the grid into the building and is credited \$0.05 kWh^{-1} for electricity that travels from the building to the grid. At these rates, the Oberlin PV installation produced energy with a total value of \$2,600 in 2003.

Like many commercial facilities, Oberlin College pays the electrical utility an additional "demand charge" based on the peak demand for any 15-minute period in the monthly billing period. This charge is \$6.25 kVA^{-1}, which is equal to \$6.25 kW^{-1} (assuming a power factor of 100%). The demand charge complicates the monetary value of PVs because this charge can effectively benefit the array's financial value if PV output coincides with peak demand.

In the case of the AJLC, the demand charge is substantial. Peaks and their resulting charges constituted 65% of total electric bills from March, 2001 to April, 2003 (Pless and Torcellini 2003). Demand charges result in a seemingly paradoxical situation. The AJLC has been a net exporter of electricity onto the electrical grid during the months of June, July and August of every year since the PV array was installed. However, because the demand charges exceed the value of this exported electricity, the College has paid electricity bills for the building during every month of operation.

The ability of the Oberlin installation to reduce the demand charge by "peak shaving" could significantly reduce financial payback. This has been previously studied. In July and August, 2001, PV output was coincident with peak demand, reducing the AJLC's load by 10 kW in each case (Pless and Torcellini 2003). The savings for the AJLC was $125, given the demand charge at that time. Since this represents a relatively small percentage of income generated by the PV production, we assume in our calculations of monetary payback that demand reductions due to PV output are negligible.

An additional complication in our analysis occurs because, while the panels were installed and began exporting electrical energy onto the grid on Nov. 14th, 2000, the utility did not install a billing meter capable of measuring excess power exported from the building to the grid until Apr. 10th, 2002. So during this initial period we were only effectively credited for solar production that was used within the building (about 46% of total energy produced). This resulted in a total dollar loss of $1,650 in un-credited energy exports for the period in question (Pless and Torcellini 2003). This represents a genuine loss of revenue for Oberlin College. However, since it resulted from problems unrelated to the PV installation itself, for the purpose of assessing monetary payback, we consider this money legitimate revenue that can be credited towards payback.

A variety of assumptions are incorporated into our calculations of financial payback times. We make the same assumptions regarding panel degradation and panel lifespan that were made in determining energy payback. At this point, predicting future prices of electricity is a highly uncertain endeavor. If the price of energy in Oberlin increases faster than inflation then the financial payback for the panels will decrease. For this analysis we assume that the price of electricity remains constant at $\$0.05\ \mathrm{kWh}^{-1}$ for the lifespan of the panels. We therefore estimate total revenues of $59,700 and $87,700 for 25- and 40-yr lifespans, respectively. Our calculations thus indicate that the initial cost of $385,778 is never recovered.

5.3 Payback with Green Attributes

Oberlin College could augment its revenue stream by selling the green attributes associated with electricity produced by the PV installation. Typical rates for wholesale PV attributes are quite variable, ranging from $\$0.02\ \mathrm{kWh}^{-1}$ to $\$0.08\ \mathrm{kWh}^{-1}$ (Jones 2004). Given the base value of electricity of $\$0.05\ \mathrm{kWh}^{-1}$, sale of the green attributes could increase revenues by 40-160%. Since Oberlin College is currently interested in purchasing green attributes, one could argue that the financial value of the PV array is already being realized (though not counted in the simple payback calculations above). Assuming the higher value of $\$0.08\ \mathrm{kWh}^{-1}$, Oberlin College received a potential value of $4,100 worth of green attributes in 2003. If we assume that this value remains constant, then energy and attribute revenues combined amount to $83,600 and $227,900 for 25- and 40-yr system lifespans. Thus, even with attributes included, initial costs are not recovered.

5.4 Payback with externalities

The market price of electricity does not currently include the very real economic costs of environmental and health damage associated with generation. One approach to assessing the Oberlin installation is to estimate the monetary value of the damage avoided when fossil fuel energy is replaced with solar-powered electricity. Although challenging and somewhat subjective, a number of studies have attempted to assess the externalized costs of electrical energy. A comprehensive review of previous studies concluded that most focus on a relatively narrow range of environmental and health effects and thereby substantially underestimate total external costs (Ottinger 1991).

We conducted analyses to estimate external environmental and health costs associated with manufacturing the Oberlin array and the externalized costs avoided through subsequent PV energy production. First, we used values reported in previous studies (Ottinger 1991) to estimate lbs of various pollutants (CO_2, SO_2, NO_X, etc.) produced per kWh of electricity generated in locations where parts of the Oberlin PV array were produced and in the local Oberlin mix. Next, we used conversion factors reported in a second study (Koomey and Krause 1997) to estimate the dollar value of environmental and health costs of these pollutants. The environmental and health costs associated with the materials and processes involved in PV production are estimated to be relatively small (Alsema and Nieuwlaar 2000). We therefore assumed that all externalities associated with PV production are attributable to energy consumed in the process. For simplicity, we also expressed the energy of BOS components in electrical units so that we could use the same general analysis to assess all environmental costs. We further assumed that the characteristics of power plants of each fuel type in all locations were identical to those described in Ottinger et al. (1991) in terms of efficiency (kWh output per BTU input), sulfur content in fuels and line losses. We estimate that external costs of the Oberlin installation range from $11,000 to $105,000. Using the same methods, we estimate that the external environmental and health costs of the electricity available in Oberlin range from $0.04 to $\$0.54\ \mathrm{kWh}^{-1}$. In keeping with our stated bias, we used the higher costs for both the manufacture of the PV installation and for the energy displaced through PV production in our estimations. We calculate that in 2003 Oberlin's PV system was responsible for averting $27,700 worth of health and environmental damage. The total value of the panels in averting environmental damage amounts to $643,500 and $944,800 for 25- and 40-yr lifespans, respectively.

TABLE 1: SUMMARY OF CALCULATIONS ON MONETARY AND ENVIRONMENTAL PAYBACK

Currency	Initial Costs	Total Revenues	Payback Time	Revenue / Cost Ratio
Secondary Energy	369 MWh	1,194 – 1,753 MWh	7.3 yrs (Feb. 2008)	3.2 – 4.8
CO_2	409,800 lbs	2,582,000 – 3,791,000 lbs	3.7 yrs (July 2004)	6.3 – 9.3
Money simple	$385,788	$59,700 -- $87,700	Never	0.15 – 0.23
Money w/ green tags	N/A	$83,600 -- $227,900	Never	0.22 – 0.59
Money w/ externalities	$391,000 -- $492,000	$68,100 -- $1,032,500	16.8 yrs (Aug.2017)	0.18 – 2.68

6. CONCLUSION

Producing electrical energy from sunlight is exciting, but it is only useful if benefits exceed costs. Our study suggests that the revenue to cost ratio can differ significantly for different currencies. For example, because of the dominance of coal as a fuel source in the region of installation, the Oberlin system pays back CO_2 relatively rapidly. On the other hand, because of the poor solar resources in North East Ohio and the relatively inexpensive cost of electrical energy in this region, this installation will never pay back financial costs in the current market environment. One obvious conclusion to draw from this analysis is that under current market conditions, PVs are a bad financial investment in Oberlin, Ohio. Alternatively, one might just as well conclude that because they begin reducing the net release of greenhouse gases into the atmosphere starting after just 3.7 years, and because energy revenues exceed costs after 7.3 years, this installation represents an excellent environmental investment over its 25-40 year lifespan. The differences in the payback times for the different currencies is interesting because it suggests that economic and environmental values are poorly aligned. Because of the challenges involved, externalized costs are the roughest component of our analysis. Nevertheless it appears clear that until and unless greater legislative efforts are made to incorporate environmental costs into the prices of energy, it will be difficult for solar technology to compete economically in large regions of the U.S.

Another major conclusion of our study is that place matters. It is obvious that solar resources are critical to energetic payback times. However, fuel sources in the location where PVs are manufactured and in the location where they are installed are no less crucial in calculating environmental value. A PV system constructed in a region dominated by renewable energy and deployed in a region dominated by coal power will be of great benefit to the environment, while a system built with coal power and deployed in a region dominated by renewable power will be a net cost to the environment.

Lastly, we conclude that when grid-connected PV technology is used to provide power for a building, its value can be maximized by carefully considering the rate structure of the utility and synchronizing building consumption with solar electric output. For the Oberlin array, an opportunity remains for developing a control strategy to more effectively dampen peaks, thereby reducing the substantial demand charge. This would effectively increase the economic value of the PV system.

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