The Net Present Societal Benefits of Rooftop Solar Photovoltaic Systems: A UC Berkeley Case Study

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ABSTRACT

Implementations of distributed solar photovoltaic technologies provides consumers the co-benefits of electricity services and carbon emissions reductions. In addressing climate change, these solar photovoltaic technologies benefit society by reducing the risks of facing environmental damages resulting from the increasing carbon concentrations in the atmosphere. While this environmental benefit is valuable, distributed solar photovoltaic systems have a higher levelized cost of electricity (LCOE) than fossil-fuel-powered generators that produce and sell their electricity to the grid in large quantities. In order to analyze tradeoffs between the environmental gains and financial costs of generating electricity from distributed solar photovoltaic systems, I constructed a site-specific cost-benefit analysis to evaluate the societal costs and environmental benefits of the systems at UC Berkeley from June to November 2016. Furthermore, my study projected twenty-year societal costs and benefits to reveal the net present societal benefits of the systems studied. Based on the current wholesale electricity prices and the costs of the systems, the benefit-cost ratio from June to November 2016 was 0.36, which indicated that the systems impose more costs on society than benefits. Future projections suggested that changes in wholesale electricity prices only contributed minimally to reducing the systems' societal cost. To cost-efficiently incentivize electricity generations from distributed solar photovoltaic technologies, policymakers need to design subsidies that spur technological innovations to lower this technology's LCOE, while valuing the environmental, health, and grid-balancing benefits derived from the marginal amounts of electricity provided by distributed generations of solar photovoltaic systems.

KEYWORDS

renewable energy economics, cost-benefit analysis, renewable energy policy, social costs of carbon, renewable energy, grid integration

INTRODUCTION

Rooftop solar photovoltaic systems, a form of distributed energy generation, convert sunlight into electricity without emitting greenhouse gases. By curtailing carbon dioxide emissions associated with energy generation, these technologies generate environmental benefits, which in turn reduce societal risks associated with climate change (Pepermans et al. 2005). The reduction in societal risk is a form of societal benefits which can be evaluated economically to inform the cost-efficiency of rooftop solar photovoltaic systems. Social Cost of Carbon (SCC), a conceptual cost defined in environmental economics literatures, is used to monetize the societal benefits associated with reducing carbon dioxide emissions (Greenstone et al. 2013). This monetization is useful for comparing the tradeoffs between reducing the negative impacts of carbon dioxide emissions and the financial costs of implementing emissions abatement technologies, such as solar photovoltaic systems (EPA 2013, Greenstone et al. 2013). In addition to considering environmental benefits, evaluations of rooftop solar photovoltaic systems' societal benefits should account for their financial costs to society. This technology's costs of electricity generation are higher than conventional fossil fuels because its Levelized Cost of Electricity (LCOE), the total cost of installing and operating this technology averaged over total electricity production in its lifetime, is greater than that of conventional fossil fuels (Baker et al. 2013, Borenstein 2008). While ample literatures documented the private financial benefits of solar photovoltaic systems, which are the savings experienced by the consumers of solar energy due to federal subsidies, they did not provide information on the tradeoffs between the societal benefits and the societal costs of this technology. In this study, I established a framework for evaluating the societal benefits of distributed solar photovoltaic systems.

Since 2011, subsidy policies, such as the federal 30% Investment Tax Credits (ITC), coupled with financing mechanisms, such as Power Purchase Agreement (PPA), drove an increase in the installations of rooftop solar photovoltaic systems, especially in California (SEIA 2016). As of 2015, California hosted half of all the United States' installations of rooftop solar photovoltaic systems (Borenstein 2015). While the abundant solar resource in California made it geographically-favorable for installing solar photovoltaic systems, PPA alleviated the burden of large upfront costs and allowed homeowners to install solar photovoltaic systems affordably. Under a PPA, a private solar firm owns the system and pays the upfront costs of installation.

Households then enter the PPA with such firms to purchase electricity from their rooftop solar photovoltaic systems at a cheaper rate than purchasing electricity from their utility companies (Davidson et al. 2015). This financing mechanism applies to a wide range of properties, including public institutions such as the University of California, Berkeley, the site of this study. The University pays lower rates for its electricity from the solar provider than from its regional utility company, PG&E. This allows the University to earn private financial benefits through these aggregated savings, which motivated the University's decision to install the systems (Borenstein 2008, 2012). However, the University did not consider the societal benefits in its decision-making process, which I determined in this study by employing a Cost-Benefit Analysis (CBA) (Borenstein 2015). My findings indicated whether these systems are, in fact, beneficial at the societal scale in addition to the institutional scale.

My central research question is: what are the societal benefits of the solar photovoltaic systems installed on the MLK Student Union and Eshleman Hall over their contract period? To answer this question, I determined the differences in monetary values between generating electricity from the solar systems versus procuring it from California's wholesale electricity market, which I defined as net production costs. I additionally computed the societal benefits by examining the external environmental benefits resulting from carbon dioxide emissions reductions from the systems; these benefits were external because they are not internalized by the costs of producing electricity (Callaway et al. 2015). This CBA incorporated both the production costs and external environmental benefits of the solar photovoltaic systems in order to calculate the net societal benefits of the systems. This holistic CBA model has a broader application value by which future research might assess the net societal benefits of other site-specific rooftop solar photovoltaic systems. In this way, findings of this study will inform policymakers on designing subsidies that effectively reward consumers of solar electricity based on the net societal benefits of their systems.

Case study background

UC Berkeley installed two sets of solar photovoltaic systems with a total capacity of 17 kilowatts on the rooftops of Eshleman Hall and MLK Student Union in December 2015 in an effort to achieve the UC-wide "Carbon Neutrality by 2025" Goal. This Goal mandates the University to reduce its carbon dioxide emissions from energy usage. In operations since 2015, these systems generate an average annual output of 150 megawatts hours (MWh) of energy, displacing fossil-fuel-generated electricity that otherwise emits carbon dioxide (Office of Sustainability 2015). The University entered a twenty-year PPA with its solar provider, SunEdison, and the University currently purchases the solar electricity at lower rates from SunEdison than it does from PG&E. The discounted rate of electricity resulted from SunEdison's installing and owning many rooftop solar photovoltaic systems across California, and the increasing scale of ownership reduces its installation costs, according to the theory of economy of scales. Furthermore, SunEdison also claims the 30% federal ITC as a financial benefit, which it then transfers to the University in the form of lower electricity rates (Taylor 2008). In this agreement, the University not only saves costs on purchasing electricity, it also advances its Carbon Neutrality Goal. While these two private benefits motivated the University's decision to install these rooftop solar photovoltaic systems, the societal benefits of these systems remained uninvestigated.

Literature review: cost-benefit analysis of solar photovoltaics technologies

Researchers in the fields of energy and environmental economics have conducted cost-benefit analysis (CBA) to understand the societal benefits of rooftop solar photovoltaic systems by accounting for their environmental benefits (Callaway et al. 2015). However, these researchers relied on CBA that generalized over large spatial scales, such as the state of California, and accordingly did not account for the net production costs and external environmental benefits associated with site-specific rooftop solar photovoltaic systems. Researchers emphasized that this lack of specificity needs to be addressed, because the location of specific systems determined the fossil-fuel-powered generators that the solar photovoltaic systems displace, which influenced the associated carbon dioxide emissions reductions (Baker et al. 2013, Borenstein 2008, 2015, Callaway et al. 2015, Roth 2004). Site-specific research required granular data; as the granularity of data was available for my case study, my research methodology aimed to generate a CBA model that accounted for both the net production costs and external environmental benefits of these solar photovoltaic systems at UC Berkeley.

Study methodology

My CBA compared the trade-offs between installing these solar photovoltaic systems in 2015 and the counterfactual of not installing them at all. I computed the net production costs of electricity from these systems for my study period, June to November 2016. Since there are many firms in the distributed generation of solar energy industry, these firms function in a competitive market where each firm makes zero economic profit in the long-run. Therefore, I assumed the contract prices for solar electricity, between the University and SunEdison, are a proxy for the market prices for solar electricity from distributed solar photovoltaic systems. Over the contract period of twenty years, SunEdison would recover its costs by charging the University the contract prices, which indicated that the aggregated payments represent these systems' net economic costs.

The result from this calculation quantified the costlier way of generating electricity from rooftop solar photovoltaic systems, which I defined as the net production costs to society. To estimate the costs beyond my study period, I obtained the rate of increase in wholesale electricity prices for the next twenty years from the United States' Energy Information Administration's (EIA) reports. The estimated wholesale electricity prices inform whether generating electricity from rooftop solar photovoltaic systems would become as affordable as purchasing it from the wholesale market. After estimating the net production costs, I discounted them by the annual interest rate of 2.5%, which was consistent with the SCC discounting rate, to obtain the net present production costs of the systems.

Additionally, I accounted for environmental tradeoffs in my CBA by considering the carbon dioxide emissions associated with fossil-fuel generations less the carbon-emission-free generations from the solar photovoltaic systems. Over the contract period, I assumed an annual degradation rate of 0.5% for the solar photovoltaic systems' electricity productions, and I adjusted each year's productions accordingly (Borenstein 2015). With the adjusted productions, I employed Marginal Operating Emissions Rates to estimate the associated carbon dioxide emissions reductions resulted from the solar photovoltaic systems for each year (Callaway et al. 2015). I converted the avoided carbon dioxide emissions into a monetary value that represented the external environmental benefits of these systems by multiplying the aggregated amount of emissions by the Social Costs of Carbon (SCC) (Callaway et al. 2015, EPA 2013, Graff et al. 2014, Greenstone et al. 2013). I also discounted the aggregated external environmental benefits by an annual interest rate of 2.5% to obtain the net present environmental benefits.

In addition to quantifying the external environmental benefits in my CBA model, it is important to mention California's adoption of time-of-use electricity rates and its impact on valuing marginal amounts of electricity produced by distributed generation of solar photovoltaic systems. Time-of-use electricity rates allow consumers to face the differences in prices between on-peak and off-peak hours, which creates a more accurate measure for the marginal values of electricity produced during different hours of the day. This will augment the benefits of electricity generated from solar photovoltaic systems, especially when the electricity generated offsets the consumers' need to purchase electricity from the grid during peak hours (Blonz 2016 and Borenstein 2012). By incorporating financial and environmental tradeoffs and assuming an annual interest rate, an annual degradation rate, and a rate of growth in wholesale electricity prices in my cost-benefit analysis, this economic model adopted elements of economic modelling to evaluate the net present societal benefits of specific rooftop solar photovoltaic systems sites uniquely and effectively.

METHODS

Computing net production costs

I employed the framework of a Cost-Benefit Analysis (CBA) to incorporate both the net production costs and the external environmental benefits of UC Berkeley's solar photovoltaic systems, and ultimately assessed their net present societal benefits. To calculate the net production costs, I first collected hourly price data, measured in \$/MWh and reported as Locational Marginal Prices (LMPs) from the California Independent System Operators' (CA ISO) Day Ahead Market. I found LMPs that are specific to Berkeley, divided them by 1,000 to obtain the data in the unit of \$/kWh. I used LMPs as a proxy for comparing to the annual contract prices (\$/kWh) between the University and SunEdison, which I collected from UC Berkeley's Office of Sustainability. Once I collected both prices datasets, I used Excel to compute the differences between LMPs and the contract prices from June to November 2016.

Upon discovering the prices differences, I calculated the costs of these systems by multiplying hourly price differences by hourly systems' electricity productions, measured in kWh. I collected energy production data, measured in 15-minute intervals, from June to November 2016. I then summed each 15-minute interval to hourly intervals in order to obtain hourly electricity productions, and matched the hourly productions with the prices differences between PPA prices and LMPs. By multiplying the hourly productions with the hourly price differences at the hourly temporal scale over the six months, I computed the net production costs to society, measured in dollars, of generating electricity from these solar photovoltaic systems (Figure 1).

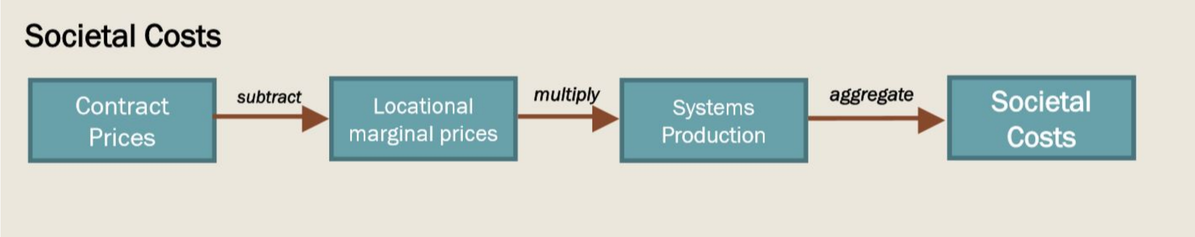

Figure 1. Conceptual model of calculating net production costs of UC Berkeley's solar photovoltaic systems.

Computing societal benefits

To calculate the societal benefits generated from the tested systems as measured by carbon dioxide emission reductions, I collected the systems' hourly electricity generations, calculated their hourly marginal emissions, and applied the Social Costs of Carbon (SCC) to obtain the monetary values of the external environmental benefits. I obtained the Marginal Operating Emissions Rates (MOER), which is an estimation model that calculates the avoided carbon dioxide emissions of time-specific electricity generated by these solar photovoltaic systems at UC Berkeley (Callaway et al. 2015). This model is constructed and owned by WattTime, a Bay-Area startup that provides software to help large facilities reduce their carbon dioxide emissions. Given both the hourly productions (kWh) and MOER (metric ton of Carbon/ kWh), I computed the hourly avoided emissions by multiplying the productions by the emissions rates. Once I obtained the avoided emissions (metric tons of Carbon), I monetized them by multiplying the EPA's SCC values ($/ metric ton of Carbon). The results, measured in dollars, represented the external environmental benefits of reducing every metric ton of carbon dioxide (Figure 2).

Figure 2. The conceptual model for calculating external environmental benefits.

Future projections and discounting

I projected the societal costs and benefits of these solar photovoltaic systems based on the derived net production costs and external environmental benefits from June to November 2016, in order to determine the long-term societal benefits of these systems. Currently, solar photovoltaic systems' productions degrade at 0.5% annually, and I adjusted UC Berkeley's systems' annual productions accordingly (Borenstein 2015). Because California's electricity market will be dynamic in the next twenty years, it is impossible to predict the prices of electricity in the wholesale market. Therefore, I bounded my projections on the wholesale prices by the Energy Information Administration and Cook's analyses on the increase of wholesale electricity prices to be between 1.9% to 3.4% annually. Within this range of increase, I constructed three scenarios: 1.9%-increase, 2.6%-increase, and 3.4%-increase, and I multiplied the annual average LMP for the systems by the three different rates of increase in order to obtain the projected annual wholesale electricity prices for the next twenty years. Furthermore, I computed the difference between contract prices and projected annual wholesale electricity prices ($/kWh), and I multiplied the differences by projected annual electricity productions (kWh) to arrive at the estimated annual societal costs for the next twenty years. I then discounted each annual societal cost according to the baseline of 2016 at a discount rate of 2.5% in order to obtain the net present societal benefits (Figure 3).

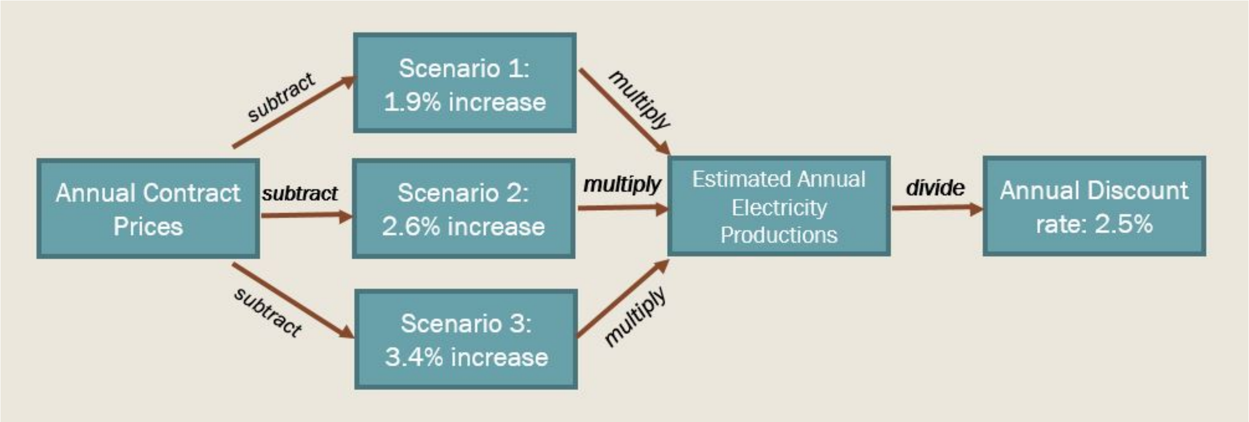

Figure 3. The conceptual model for projecting the future costs and discounting them to obtain the net present societal costs of the systems in dollars.

In terms of estimating the societal benefits, I assumed the same marginal emissions rates in my future projections for electricity from the gird because the emissions rates depend on the profile of generation sources in California during the next twenty years, which is unpredictable. By multiplying the marginal emissions rates by the projected electricity productions, I obtained the estimated avoided carbon emissions (metric tons). SCC estimates the associated marginal damages of every metric ton of carbon emission emitted over the next twenty years. I multiplied the annual SCC with the corresponding estimated annual electricity productions to monetize the external environmental benefits of the systems, measured in dollars. I then discounted the annual benefits by 2.5% to yield the net present external environmental benefits of the systems (Figure 4). Lastly, I computed the benefit-cost ratio by dividing the net present external environmental benefits by the net present production costs.

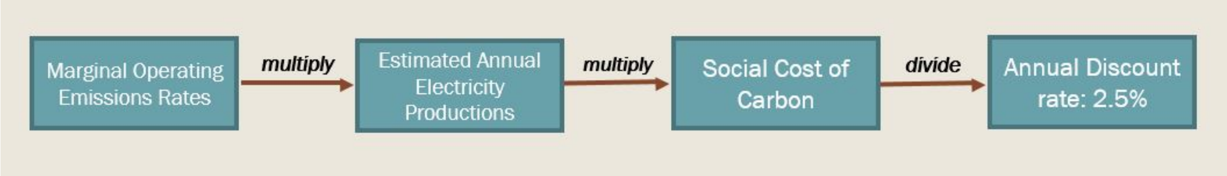

Figure 4. Projecting external environmental benefits for the next twenty years involves holding the Marginal Operating Emissions Rates constant.

RESULTS

The net production costs

Comparing the solar photovoltaic systems' contract prices to CA ISO's wholesale Locational Marginal Prices revealed that producing and consuming electricity from distributed generation of solar was costlier than purchasing electricity from the grid. The difference between the two prices varied due to seasonality, which resulted in differences in the monthly net production costs to society. For instance, June was in the middle of summer and therefore the solar systems received a large amount of sunlight and produced more electricity than any other months. The increase in solar electricity production due to this seasonal variation explained the higher net production costs in June. Furthermore, there was a downward-sloping trend in the net production costs from June to November, which tracked a decrease in solar energy production as the amount of available sunlight decreased in winter (Figure 5).

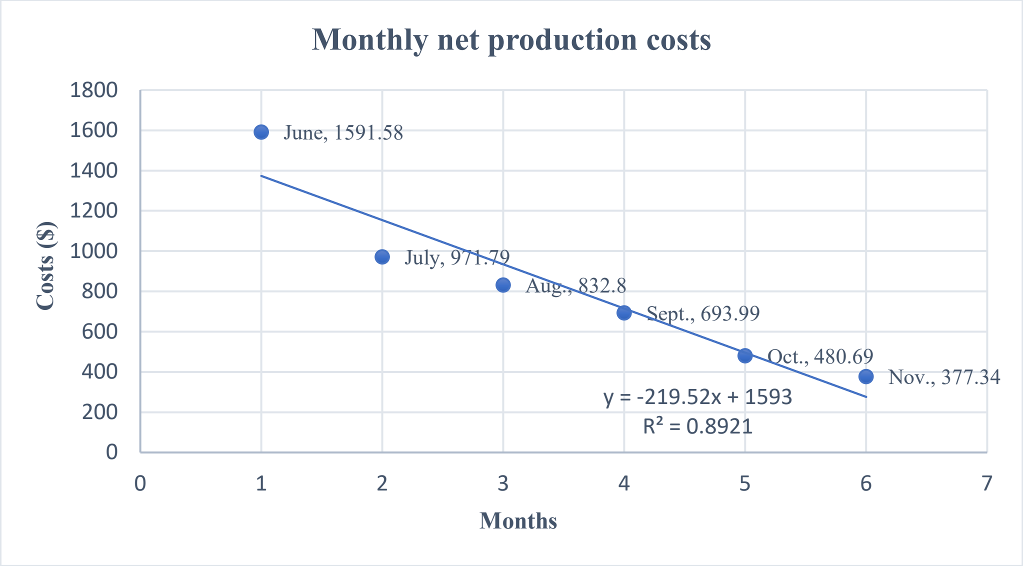

Figure 5. Societal Costs from June to November 2016. Societal costs decreased with available sunlight due to seasonal variation and the resultant reductions in the solar system's productions.

The external environmental benefits

Applying Marginal Operating Emissions Rates (MOER) to estimate the hourly avoided carbon dioxide emissions generated by the solar systems tested, I quantified the carbon dioxide emissions reductions in metric tons from June to November 2016. I then multiplied the emissions reductions by the US EPA's Social Cost of Carbon for 2016, which was $67.64/metric ton, and obtained the monetary value for the resulting external environmental benefits from these solar photovoltaic systems (Table 1). Similar to the downward-sloping trend found in the net production costs of the systems, the avoided carbon dioxide emissions also exhibited a downward-sloping trend (Figure 6).

Table 1. Monthly Carbon Dioxide emissions reductions and corresponding societal benefits.

Months	CO2 reductions (tons)	Societal Benefits ($)
June	8.17	552.62
July	5.24	354.43
Aug.	4.87	329.41
Sept.	3.71	250.94
Oct.	2.39	161.66
Nov.	1.71	115.66

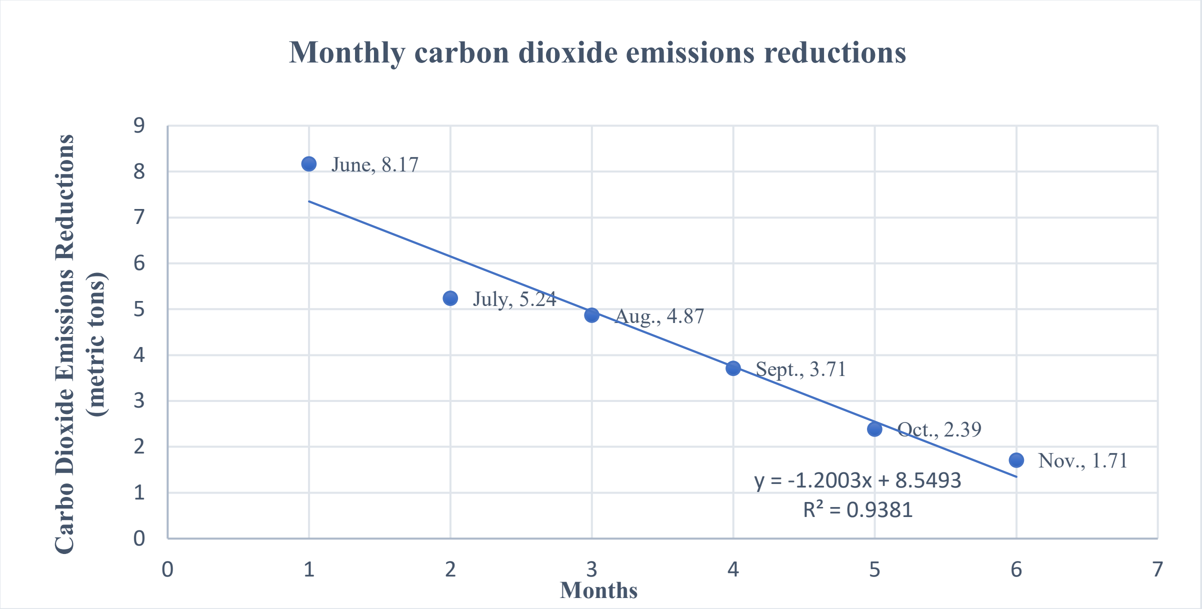

Figure 6. Carbon Dioxide emissions reductions from June to November 2016. Emissions reductions decreased corresponding to the decrease in energy production.

The cost-benefit analysis: Net societal benefits

The net societal benefits of the solar systems tested from June to November were calculated and expressed as the differences between the monthly net production costs and the net external environmental benefits. From June to November 2016, this set of solar photovoltaic system produced a net societal benefit of -3183.47 dollars (Table 2).

Table 2. Monthly societal costs, societal benefits, and net societal benefits.

Months	Net production Costs ($)	External Environmental Benefits ($)	Net Societal Benefits ($)
June	1591.58	552.62	-1038.96
July	971.79	354.43	-617.36
Aug.	832.80	329.41	-503.39
Sept.	693.99	250.94	-443.05
Oct.	480.69	161.66	-319.03
Nov.	377.34	115.66	-261.68

Twenty-year projections: Net present societal costs and benefits

Different growth rates in California's wholesale electricity prices yielded different net present production costs of the systems. In Scenario 1 with an annual 1.9%-increase, the net present production costs of the systems over the next twenty years was $182,000. Whereas, in Scenario 2 with an annual 2.6%-increase, the net present production cost was lower than that of Scenario 1 at $178,000. Lastly, the annual 3.4%-increase in Scenario 3 resulted in the lowest net present production cost of $171,000. On the other hand, the external environmental benefits of the systems over the next twenty years totaled to 1,043 metric tons of carbon dioxide emissions reductions, which translated to $66,400. My projection resulted in net present societal benefits of -$116,000, -$112,000, and -$105,000 in Scenarios 1, 2 and 3 respectively. In addition, the resulting benefit-cost ratios for Scenarios 1, 2 and 3 were 0.365, 0.373, and 0.383, respectively.

DISCUSSION

In my study, I calculated the societal costs and benefits of the solar photovoltaic systems on MLK Student Union and Eshleman Hall at UC Berkeley by comparing the net production costs and external environmental benefits to society, in order to understand the economic efficiency of generating carbon-emission-free electricity from this technology. Given the higher levelized costs of electricity (LCOE) of distributed generation of solar energy, my study confirmed that it is costlier to society to generate electricity from these systems than purchasing electricity from the grid (Borenstein 2008, 2015 and Roth 2004). However, there were also external environmental benefits associated with generating electricity from solar photovoltaic systems, which reduced part of their societal costs upon internalizing them in my analysis (Pepermans et al. 2015). Taken into consideration the net production costs and the net external environmental benefits, the benefit-cost ratio of 0.36 revealed that it was unbeneficial to install these solar photovoltaic systems today, because they posed more costs than benefits on society. To provide a more holistic understanding on the societal costs and benefits over their contract period of twenty years, I estimated the future benefit-cost ratios in three scenarios of low, medium, and high growth rates in California's wholesale electricity prices. These benefit-cost ratios would be slightly higher than 0.36, but would not be enough to offset the net production costs.

The societal costs: net production costs

For this case study, the societal costs of producing and consuming electricity from distributed generation of solar energy were more expensive than purchasing that electricity from the grid. From June to November 2016, my study found that the systems were costlier at generating electricity by an aggregated margin of $4,950. Decomposing this aggregate net production cost, I determined that June and July were months that contributed the most to the high production costs. Since the production costs were calculated directly from multiplying the systems' productions by the differences between marginal wholesale electricity prices and the systems' contract prices, the higher net production costs resulted from the more abundant electricity generation in June and July due to greater solar insolation. This result may seem puzzling, because it suggested that as productions from these solar systems increase, the costs of its electricity also increased, which seemed to contradict the theory of economy of scales. However, one caveat to this contradiction was to consider the difference between wholesale electricity prices and the contract prices of the solar systems as a negative externality. This negative externality resulted from the fact that society is generating and consuming electricity from a more expensive distributed generation of solar energy instead of from a cheaper source, such as buying electricity from the grid (Borenstein 2008).

After computing the net production costs of distributed generation of solar energy, it is worth discussing why many homeowners still choose to install them. The federal Investment Tax Credits (ITC) created positive private benefits that incentivized homeowners to install rooftop solar photovoltaic systems. Borenstein emphasized the importance of distinguishing between private and societal benefits of generating carbon-emission-free electricity via distributed generation technologies; he calculated the private benefits that the consumers of rooftop solar electricity gained, and found them to be positive (2012). This meant that the consumers face a lower electricity bill as a result of installing solar photovoltaic systems, which in turn motivated their decision to adopt this technology. This form of net private benefits was also observable in my case study, where the contract prices for electricity are lower than the tariff rates that the University pays PG&E (Office of Sustainability 2015). While the federal ITC provided positive private benefits to homeowners, society still incurs the true costs of generating electricity from these systems.

The external environmental benefits

Avoided carbon dioxide emissions from electricity generated by solar photovoltaic systems are a prominent environmental benefit. Quantifying the avoided carbon dioxide emissions also contributes to broader climate change mitigation goals - especially in California, where the State needed to reduce its GHG emissions according to Assembly Bill 32 (Taylor 2008). I employed the Marginal Operating Emissions Rates (MOER) to compute avoided carbon dioxide emissions, and found that from June to November 2016, the systems avoided 26 metric tons of carbon dioxide emissions. Expectedly, the months with large electricity productions, June and July, also yielded the most reductions in carbon dioxide emissions. Callaway et al. used MOER for a similar purpose, where they estimated the environmental benefits of all solar systems across California by aggregating the marginal avoided carbon dioxide emissions from each system (2015).

Calculating marginal amounts of avoided carbon dioxide emissions is important for the accurate accounting of environmental benefits, because distributed generation of solar photovoltaic systems only supply electricity to the grid in marginal amounts since they produce less electricity compared to natural gas plants. The use of marginal emissions reductions is not only relevant to solar photovoltaics energy economics, but is also important in evaluating the environmental benefits of electric cars. GraffZivin et al. developed a methodology to estimate the marginal carbon dioxide emissions of electricity generators across the United States, in order to capture the variability in emissions intensity due to time-of-day for electricity demands and locations of the generators. This model allowed them to quantify the carbon emissions associated with charging electric vehicles, which helped inform the cost-efficiency of subsidy policies for electric vehicles (2014).

Valuing avoided carbon dioxide emissions is controversial, because it raises questions about the validity such estimations (Greenstone et al. 2013). I adopted US EPA’s Social Cost of Carbon (SCC), which is widely used in the Agency’s assessment of its environmental policies, to monetize the avoided carbon dioxide emissions from these solar photovoltaic systems. Despite many scholarly debates on the use of SCC, it is a crucial tool for calculating the marginal damages associated with carbon-dioxide-emitting activities such as generating electricity via fossil fuels. Greenstone et al. argued that the SCC should be applied to evaluate cost-efficiency of environmental policies, because SCC monetizes the changes in net agricultural productivity, human health, property damages, and ecosystem services which are impacted by the increasing carbon dioxide concentration in the atmosphere (2013).

My results concluded that the external environmental benefits of the systems from June to November 2016 was $1,760, representing the risks that the society avoided because 26 metric tons of carbon dioxide were avoided. Furthermore, these systems would avoid an aggregate amount of 1,043 metric tons over its contract period, which translated to avoidances of costlier risks valued at $66,400. While the net present external environmental benefits were still less than the net production costs of these solar photovoltaic systems at UC Berkeley, these environmental benefits helped increase the benefit-cost ratio.

Benefit-cost ratio

Summing the net production costs and the net external environmental benefits from June to November 2016 yielded the benefit-cost ratio of 0.36 for these solar photovoltaic systems at UC Berkeley. A benefit-cost ratio less than 1 suggested that the project is cost-inefficient because the costs outweighed the benefits. Similarly, this result implied that it is cost-inefficient to invest in solar photovoltaic systems as a technology to provide the co-benefits of electricity services and carbon dioxide emissions reductions. While the current benefit-cost ratio of distributed generation of solar was low, increasing research and recognition of quantifying and monetizing environmental damages would likely augment the value of carbon-dioxide-emissions-reducing technologies. Anthoff and Tol modeled and quantified the social damages that other greenhouse gases, such as methane, nitrous oxides, and sulfur hexafluoride, pose on global climate change (2013). The quantifications of these damages would be useful for future research in the societal benefits of greenhouse-gases-reducing activities such as distributed generation of solar photovoltaic systems.

In addition to increasing SCC, which augments the external environmental benefits, the societal benefits of distributed generation of solar energy can be improved by reevaluating the current payment and subsidies structures. Weisbach demonstrated that subsidies for renewable energy technologies create positive externalities such as research and development of these technologies, which are important to California's goal to decarbonize its electricity grid (2013). However, Davison et al. explicated that most of the installations of distributed solar systems are under the Third-Party Ownership payment structure, which I found to impose more costs on society (2015). These two conflicting trends in renewable energy technology subsidies should prompt policymakers to reconsider their approaches to reap the most benefits from these subsidies, because the current subsidies and payment structures for distributed generation of solar photovoltaic systems do not necessarily give rise to this outcome.

Twenty-year projection: Net present benefit-cost ratios

My twenty-year projection analyzed the uncertainties in California's wholesale electricity prices and revealed how different price change scenarios influence the benefit-cost ratio of these solar systems at UC Berkeley. Cook's analysis on the wholesale electricity prices in California concluded that the prices will rise in the range between 1.9% and 3.4% annually from 2013 to 2040 (2013). This interval of increase was also supported by the EIA in its Annual Energy Outlook (2016). Furthermore, EIA and Birge et al. explained that the future wholesale electricity prices are closely tied to the trends in natural gas prices, because natural gas plants will supply the increasing electricity demand as California decarbonizes its electricity grid in order to achieve the goals set forth in Assembly Bill 32 and Renewable Portfolio Standards (2016 and 2014).

After modeling these three different rates of increase in wholesale electricity prices in California over the next twenty years, I discovered that the net present benefit-cost ratios are 0.365, 0.373, and 0.383, respectively for Scenarios 1, 2, and 3. This means that these systems will still incur more costs on society than the environmental benefits that they generate over the next twenty years. While the benefit-cost ratios appear to increase from Scenarios 1 to 3 as the wholesale prices increase, the changes in wholesale electricity prices alone will not contribute enough benefits to outweigh the net production costs of solar electricity. This suggest that the costs of distributed generation of solar photovoltaic systems would need to decrease in order for the technology to become cost-efficient at providing carbon-emission-free electricity.

Limitations and future directions

The two major limitations of my study were the unpredictability of wholesale electricity prices in California, and the focused scope of accounting for only the carbon dioxide emissions reductions benefits. The prices volatility is an unavoidable limitation in any future projections of wholesale electricity, since there are uncertainties in the generation profile and the generation costs of electricity from different sources over the next twenty years. While it remains impossible to predict the future of electricity prices, additional investigation is warranted on how California's adoption of time-of-use retail electricity rates increases the value of renewable energy, because the value of marginal solar electricity will increase (Blonz 2016 and Borenstein 2012).

The second limitation might be addressed in future study by accounting for other societal benefits such as improved air quality from the avoided emissions of carbon dioxide. One could use Anthoff et al.'s model for the social costs of other greenhouse gases to monetize health benefits from the avoided emissions of other pollutants (2013). The incorporation of health benefits will yield a more comprehensive evaluation of the societal benefits of distributed generation of solar technologies. Lastly, one could apply the cost-benefit analysis model built in this paper, and sample more solar systems that have different ranges of capacity and are in different regions of California. This would allow for the construction of a profile of solar systems' net present societal benefits, and enhances the model's reproducibility and applicability.

Broader implications

Evaluating the net present societal benefits of distributed generation of solar photovoltaic systems is important for both understanding the economics of renewable energy, and for designing cost-efficient policies that encourage more generations of carbon-emission-free electricity from solar photovoltaic technologies. My cost-benefit analysis model uniquely evaluates the economic efficiencies of distributed generation of solar photovoltaic systems, namely rooftop solar. Since the economic efficiency of solar systems is contingent upon the wholesale electricity prices, the costs of the systems, the social costs of carbon, and the marginal emissions rates of the electricity from the grid, this model disentangled the interactions between these variables and determined their impacts on the systems' economic efficiency. This model may be used in future research with the purpose of evaluating more distributed generation of solar photovoltaic systems to reveal their aggregate true costs to society.

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