Paper ID APEN-MIT-2019_155
Applied Energy Symposium: MIT A+B
May 22-24, 2019 • Boston, USA

A comparative analysis of economic and environmental tradeoffs of roof-mounted solar plants for manufacturing locations in the U.S.

Amir T. Namin
Department of Mechanical & Industrial Engineering
Northeastern University
Boston, USA
anamin@coe.neu.edu

Sagar Kamarthi
Professor, Department of Mechanical & Industrial Engineering
Northeastern University
Boston, USA
sagar@coe.neu.edu

Matthew J. Eckelman
Associate Professor, Department of Civil & Environmental Engineering
Northeastern University
Boston, USA
m.eckelman@northeastern.edu

Jacqueline A. Isaacs
Dean of college of Engineering.
Department of Mechanical & Industrial Engineering
Northeastern University
Boston, USA
jaisaacs@coe.neu.edu

Abstract— Manufacturing is responsible for approximately one-third of primary energy use and 37% of carbon dioxide emissions globally. As the interest in renewable energy is growing, this study considers the economic feasibility and environmental implications of installing onsite roof-mounted solar PV systems on a case study manufacturing facility in five U.S. states (California, Florida, Indiana, New Jersey, and Texas), which have varying levels of solar irradiance, different incentives, solar policies, and manufacturing incentives at both the federal and state level. In these five cases, a combination of high efficiency SunPower solar panels (monocrystalline) with sun tracking technology are considered. The objective of this research is to compare the impact of state incentives and regulatory policies, as well as physical and locational differences, on the economic and environmental performance of high efficiency monocrystalline solar PV panels used for powering manufacturing processes.
Using NREL's System Adviser Model (SAM), common financial metrics such as the economic payback period, Net Present Value (NPV) and Levelized Cost of Energy (LCOE) are investigated considering the federal and local incentive policies for the selected states. Energy Payback Time (EPBT) and Greenhouse Gas emissions (GHG) as common environmental performance metrics for life cycle of PVs are compared for different cases. The results indicate, lower LCOE and positive NPV can be achieved under certain conditions with the economic payback time ranging from 3 to 15 years. EPBT is less than two years for the five selected states with the CO_2 equivalent abatement cost ranging from \$0.5 - \$151 per ton.

Keywords— *Sustainable manufacturing, Renewable solar energy, Economic feasibility, Environmental benefits, Policy analysis*

I. INTRODUCTION

The manufacturing and industrial sector accounts for approximately 33% of worldwide primary energy use and 37% of carbon dioxide emissions [1]. In the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), industrial sector was reported as the top pollutant end-use sector [2]. For Organization for Economic Cooperation and Development (OECD) countries, manufacturing contributes on average 16% of Gross Domestic Product (GDP), increasing to more than 30% for China and South Korea [3, 4]. According to the U.S. Bureau of Economic Analysis [5], the manufacturing sector accounts for 18% of U.S. GDP. Given its economic and environmental significance, manufacturing has long been a target of efficiency and other greening efforts. There are three basic strategies for green manufacturing [6]: 1) utilize clean energy resources 2) improve manufacturing technology, and 3) use lower impact materials. This article focuses on the first strategy: renewable energy for manufacturing, by considering roof-mounted solar PVs on industrial buildings which generally have steady load profile and flat large roof areas.

Globally, the International Renewable Energy Agency (IRENA) reported the first "technology roadmap" for Renewable Energy in Manufacturing as part of REmap 2030, which could grow renewables to 27% of total energy consumption for manufacturing globally by 2030 [7]; while, only 1.5% of electricity consumption of the U.S. manufacturing sector is generated through onsite renewable sources other than biomass (e.g., solar, wind, geothermal) [8]. Recently, and particularly after the Paris Agreement, many manufacturing firms have undertaken voluntary climate actions to meet greenhouse gas reduction targets [9]. One of the major contributors to greenhouse gas emissions is fossil fuel-based electricity generation. Hence, a key climate action has been for businesses for transition to distributed or onsite electricity generation from renewable sources. In addition to reducing emissions, distributed or onsite generation can provide businesses with strategic advantages including: secure and reliable power sources with reduced possibility of disruptions and blackouts; economical profitability by reducing energy costs and possibility of selling surplus power to utility companies; and enhanced brand reputation [10-12].

Due to improving efficiencies, economies of scale, and rapidly falling production costs, wind and solar energy technologies have become more widespread in recent years [13-16]. Levelized Cost of Energy (LCOE) values have been continuously falling for renewable energy technologies in the past years. The decrease is quite significant, such that in some cases the building and operating costs of new renewable energy projects have decreased below the operating costs of existing conventional electricity generation technologies such as coal or nuclear [17]. Additionally, community acceptance variables such as visibility of modern artefacts and structures, installed capacity, and Townsend Index score are associated with planning outcomes for onshore wind and solar farms [18]. The recent contract between Xcel Energy and steelmaker EVRAZ in Colorado, U.S. for a 240-MW solar project [19] and the world's largest lithium ion battery factory, Tesla's Gigafactory [20] are the examples of large solar power generation projects specifically serving manufacturing facilities.

Energy use in the industrial sector is highly heterogeneous, therefore, policy design and energy consumption modeling in the sector is quite challenging [21, 22]. The main contribution of this study is to the sustainable manufacturing literature to provide helpful insights for policy makers and manufacturers to facilitate the transition to renewable solar energy for the top and third largest energy consumer [23] and GHG emitter sector [24]. This study is applied a comparative policy scenario analysis to investigate the influence of different financial incentives and regulatory policies explicitly available for industrial sector on economic metrics in five U.S locations.

II. STUDY BACHGROUND

This study explores the economic and environmental impacts of utilizing roof-mounted solar PV systems on manufacturing facilities in five U.S. states (California, Florida, Indiana, New Jersey, and Texas). These states were chosen to represent a range of solar irradiance, solar policies, and manufacturing incentives. Specifically, the study explores a solar PV system for a lithium-ion battery manufacturing facility with a detailed production model [25]. The facility houses equipment for different processes (e.g., cathode and anode material mixing, calendaring/pressing, wetting/filling, forming, and testing). The total floor space required to fabricate the final product should be a minimum of *8,000m²* according to [25]. This value is close to the average enclosed floor space per establishment of *~8,500m²* for facilities under North American Industry Classification System (NAICS) code 335xxx "electrical equipment, appliance and components" sector reported by Energy Information Administration (EIA) [26]. The plant is designed to produce 1 million batteries, with a net electricity requirement of approximately *4.5 kWh* per battery, which results in electricity demand of *4.5 GWh* per year [25]. According to high efficiency monocrystalline modules manufactured by SunPower (SPR-X22-470-COM) with 22.0% efficiency and module area of *2.162m²* [27], the available roof area can accommodate mounting of approximately 3668 modules (considering the solar panel setback) with desired array size of 1.75-MW, determined by using the System Advisor Model (SAM-Version 17.9.5) developed by the US National Renewable Energy Laboratory (NREL). The rated capacity is the same for the states of interest, because the identical type of solar PV panels is considered to be utilized on an equivalent roof area of a battery manufacturing facility in each state (details in Table 1).

SAM can be categorized into the techno-economic energy simulation model which can provide helpful insights for decision makers in the renewable energy industry. The performance and financial models integrated in the SAM, have the inputs of performance characteristics of physical equipment and project cost and financial assumption. Typical Meteorological Year 3 (TMY3) as an option for weather data, which is provided by NREL's National Solar Radiation Database for solar resource data and ambient weather conditions, is used in the performance model in this study [28]. The equipment parameters provided by SAM in several libraries are in accordance with the California Energy Commission (CEC) report [29]. The simulation model runs based on hourly or sub hourly time-steps to determine the generated energy and economic metrics.

Each location is simulated using SAM [30] to assess the long-term economic and environmental tradeoffs of operating a 1.75-MW solar plant with high efficiency monocrystalline roof-mounted panels for 25 years. The economic analysis considers net present value (NPV), LCOE, economic payback period, and price of GHG emissions abatement per metric ton of CO_2 equivalent. Many of the larger manufacturing firms have set greenhouse gas emissions reduction targets in regions with qualified carbon emissions trading schemes. Such firms typically evaluate and compare the costs of reducing GHG emissions through different abatement options, using metrics such as the price per ton of CO_2 equivalent emissions abated. The environmental benefits of using onsite renewable electricity as opposed to grid electricity, are explored for reductions in GHG emissions along with nitrogen oxide (NO_x) and sulfur dioxide (SO_2) cumulative emissions. Furthermore, the Cumulative Energy Demand (CED) and expected output of

TABLE 1. Solar PV System Information

State	Cap Factor (%)	Location	Ave. Irradiance ($kWhm^{-2}$/ day)[31]	1st yr (MWh)	1st yr Demand Covered (%)
CA	26.0	San Jose	6.5-8	3980	88
FL	22.3	Miami	5-5.5	3407	76
IN	20.7	Indianap-olis	4-4.5	3175	70
NJ	20.1	Newark	4-4.5	3084	69
TX	24.3	Dallas	5.5-7	3728	83

each PV system is used to determine the energy payback time (EPBT) for each location.

III. DATA AND METHOD

The model simulates changes under availability or absence of financial incentives and regulatory policies from 2018 for 25 years, which can be expanded for trajectories beyond the studied period. Fig. 1, presents a flowchart of the model. Its inputs are cost factors such as module, inverter, Balance of System (BOS), general information including weather data, electric load, system loss, and financial parameters such as tax and insurance rates, incentives and regulations. The outputs of the model are economic factors (NPV, LCOE and economic payback period) and environmental impacts (EPBT, CO_2 equivalent abatement, and air emissions avoided). PV module efficiency plays an important role in project economics and energy payback time because higher efficiencies can reduce the number of PV modules and associated equipment including the foundation and cables [32]. In this study, high efficiency monocrystalline modules (SPR-X22-470-COM) are considered for generating onsite solar energy. These modules give 22.0% efficiency with only a 0.36% degradation rate per year [33, 34], which can contribute to reducing both EPBT and economic payback time [35, 36]. Because the energy production and efficiency of solar PV panels can be increased by 12%-20% when using sun tracking systems [37, 38], two-axis tracking solar systems are assumed in the installation; therefore, the orientation of the solar panels (tilt and azimuth) are not available to report. Electricity price escalation rates are considered according to the average annual increase in retail price of electricity for industrial sector from 2001 to 2017 in the selected states [39]. The detail of each state escalation rate is presented in Table 2. The five selected states cover a rating, by an industry organization evaluating state incentives for solar grades, ranging from A to C [40, 41]. Additionally, the percentage of total state gross products from manufacturing ranges from 5% to 30% for Florida, New Jersey, California, Texas, and Indiana, respectively [42]. Detailed information for each state including state business incentives and solar friendliness is presented in Appendix B. Financial incentives include tax credits, loan programs, Modified Accelerated Cost Recovery System (MACRS), investment and production-based incentives (IBI & PBI), and renewable energy credit programs. Tax credits are the dollar amount in tax savings that can reduce a considerable portion of the installation cost. MACRS is a five-year accelerated cost recovery system that includes a 50% first-year depreciation for renewable energy technologies. Investment and performance-based incentives are the payments that can be received at the federal or state level for the investment in or production of the solar systems respectively. Solar credits can be sold to utility companies looking to avoid penalties for not generating enough renewable energy as mandated for each state, which are determined based on Renewable Portfolio Standards (RPS). Alternatively, regulatory policies contain RPS, net metering, interconnection, Feed-in Tariff (FiT), electricity prices and solar permits [40]. RPS is a law enacted by an individual state to mandate that a specific percentage of all energy generation must be attained through renewable sources by a certain date. Net metering generally enables the customers to use the electricity generated by their systems and sends the excess energy back to the grid in exchange of credits in their current or next billing cycles. Interconnection is a set of policies related to connecting the solar system to the grid. Interconnection and net metering can be considered as a way of accounting for the changing relationship over the day between PV array output and local loads. This accounts for sending any surplus day-shift electricity to the grid, while at night, power flow is from the grid. FiT is the receivable payment for the solar energy generated in non-net metering states. The electricity price from utility companies and resulting energy costs can effect in savings through generating electricity onsite. Because regional incentives and policies could differ among different cities and utility companies, we tried to compare the general conditions of the states [40]. However, in two of the selected states, Indiana and Texas, the existing conditions present larger differences, considering different locations, cities, and utility companies. Indiana has a cap of 1-MW for a solar PV system to be eligible for net metering; however, industrial facilities could be exempt from that cap. Texas provides more flexibility in terms of negotiating the conditions of incentives and regulatory policies in different areas of the state. For instance, a solar rebate program is available in San Antonio area, and net metering can be negotiated in different regions of the state [40]. Due to the mentioned uncertainties and the importance of net metering as a regulatory policy, availability and absence of net metering in Indiana and Texas are reported in the results section. To check the model reliability, the model is fully documented for further evaluation and reproduction in the Appendix and based on the guidelines for reporting simulation-based studies [43].

ECONOMIC ANALYSES

The cost benefit analysis of developing roof-mounted PVs for a manufacturing facility is performed under both existing and the most progressive federal and state financial incentives and policies for PVs for manufacturing sector in the five selected states. To determine each economic metric, all of the cost factors for the industrial sector including purchasing PV panels, installation, BOS, Operation and Maintenance (O&M), regional electricity costs, and regional financial incentives and policies are integrated into SAM.
Details on the cost factors are presented in the Appendix A.

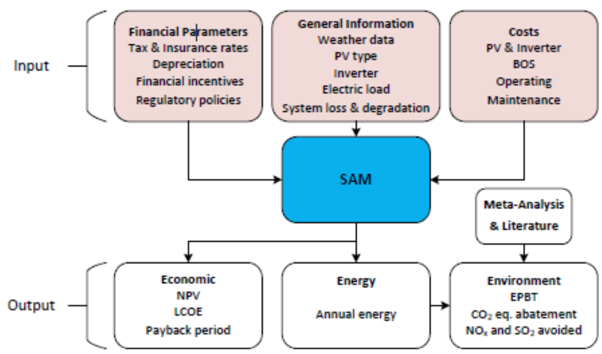

Figure 1: The process flow of data and information utilized in this study. The costs, general information, and financial parameters are used as input to NREL's SAM simulation model. The SAM model calculates the economic metrics as well as energy-related factors. The NPV and annual energy production are then used along with the other data source to determine CO_2 equivalent abatement price, EPBT, emission factors.

Despite the uncertainties associated with raw material prices, operating and investment costs over the next decades, the economic analysis still provides meaningful insights to manufacturers and decision makers on the feasibility of PV systems to power a manufacturing facility [44]. The price of CO_2 equivalent abatement is calculated based on the NPV of each investment in the states of interest. A negative or positive price of CO_2 equivalent abatement indicates losses or profits, respectively, from the investment in a solar PV system.

Environmental analyses

For EPBT estimation the CED of monocrystalline PV is used. The insights gathered from the literature [45-59] and a meta-analysis [60] are used for life cycle CED assumptions including the required energy for PV module materials, manufacturing, transportation, installation, BOS, O&M, and End-of-Life (EOL) processing. The harmonized data considering 30% electricity conversion factor to primary energy equivalent for mono-crystalline silicon with a range between 240 and 1600 and average of *645 kWh/m²* is considered for CED assumptions [59]. Furthermore, the avoided GHG and other air emissions (NO_x, SO_2) via onsite electricity generation are calculated for each eGRID sub-region [61]. GHG and other air emissions avoided (NO_x and SO_2) are calculated based on the amount of avoided electricity consumption in each eGRID sub-region with current marginal emission factors ranging 134-762 (kg/MWh) for CO_2 equivalent, 0.12-0.52 (kg/MWh) for NO_x, and 0.14-0.52 (kg/MWh) for SO_2 by assuming no change in grid electricity emission factors over the 25 year period [61].

IV. RESULTS

The cost effectiveness and environmental impacts of using 1.75-MW roof-mounted solar PV systems to power manufacturing facilities for a period of 25-year in the five selected states are assessed in this section.

ECONOMIC PAYBACK TIME

The economic payback time for renewable energy investments is compared for the five selected states for two scenarios. In the first scenario, the existing incentives and policies at the federal and state levels for solar renewable investments are considered. In the second scenario, progressive incentives imposed by the state of New Jersey, as the highest rank state in the U.S. [41], are considered for the selected states. Fig. 2, compares economic payback time for both scenarios. As expected, when the currently existing conditions of each state are used, New Jersey outperforms all other states with 3 years economic payback period due to its most encouraging incentives (solar credit/rebate program). The rebate program in New Jersey provided under a solar loan program is a PBI at the rate of $0.248 per kWh for 10 years. The second best economic payback period is 3.7 years in California. Texas is third with an economic payback time of 4.9 years. If the solar rebate program of San Antonio (0.80 $/W with the maximum of $80,000 per commercial customer) is imposed, the economic payback period in Texas drops to 4.6 years. Florida has the longest economic payback period among the five states with 14.8 years. Despite the high sun irradiance, the "Sunshine State" shows the longest economic payback time because of the absence of effective incentives and policies. Since, net metering is negotiable in some of the cities in Texas, and, there is a 1-MW cap for systems can be qualified for net metering in Indiana while the industrial sector systems might be eligible for net metering, availability and absence of this important policy is explored in this section. If net metering is not available in Texas and Indiana state-wide, then the investment would not payback in 25 years. However, when New Jersey conditions are imposed in all states, New Jersey itself takes the longest payback period of 3 years because it has the lowest average solar insolation. Under the New Jersey incentives and regulatory conditions, California would have the shortest payback time of 1.9 years, followed by Texas with 2years, Florida with 2.6 years, and Indiana with 2.7 years. Fig. 2, and Table 2 illustrate these results. Furthermore, all five states are analyzed under the following conditions: 1) no financial incentives and policies; 2) availability of only financial incentives; 3) availability of only regulatory policies; and 4) availability of both incentives and policies. With no incentives or regulatory policies, none of the states can payback the investment over the 25-year period. When only financial incentives are available, just New Jersey can pay back the investment in 3.5 years. Finally, when only regulatory policies are available, all the states except New Jersey can pay back the investment (9 years for CA, 14.3 for TX, 17.1 for IN, and 22.2 for FL), which shows the importance of generous PBI available in New Jersey.

LEVELIZED COST OF ENERGY (LCOE)

LCOE is used by SAM, the NREL's simulation tool, as an indicator of each state's financial incentives. The states with better financial incentives –not regulatory policies– would have a lower LCOE. The LCOE is calculated using (1).

$$LCOE = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_n}{(1+d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1+d_{real})^n}} \quad (1)$$

Q_n : *Electricity generated by the system in year n (kWh)*
N : *Analysis period in years*
C_0 : *Project equity investment amount*
C_n : *Annual project cost in year n*
d_{real} : *Real discount rate without inflation*
$d_{nominal}$: *Nominal discount rate with inflation*

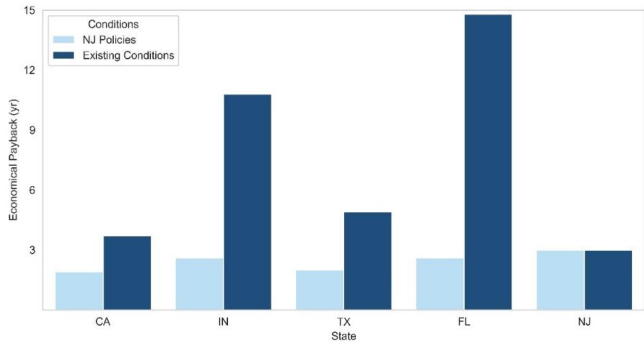

Figure 2: Economic payback time under two scenarios. In the first scenario (darker bars), each state operates with their existing financial incentives and regulatory policies as is. In the second scenario (lighter bars), the progressive financial incentives of the state of New Jersey are imposed.

C_n is the product of the LCOE and the quantity of electricity generated by the system in that year (2).

$$C_n = Q_n \times LCOE \quad (2)$$

Project costs C_n include installation, O&M, financial costs and fees, and tax benefit or liability, and account for incentives and salvage value. The annual cost C_n is nominal dollar and includes the effect of inflation as well [30]. Table 2 details the results for the LCOE and economic payback period for the five states under different conditions: 1) existing conditions; 2) absence of incentives and policies; and 3) incentives and policies based on the state of NJ. According to the LCOE formula used by SAM (NREL) [30], LCOE doesn't alter when no cash incentives, which can reduce the project equity investment, is available (this can be considered as financial incentives while regulatory policies doesn't affect the equity investment). On the other hand, incentives or policies that can reduce the entire expenditures would affect economic payback. Therefore, the LCOE results for existing conditions and availability of only financial incentives are equivalent; while, the results for availability of only regulatory policies and absence of incentives and policies are similar. Indiana has the highest LCOE under its existing condition followed by Florida and Texas at 5.23 cents/kWh, 5.14 cents/kWh, and 3.23 cents/kWh respectively. New Jersey could achieve the lowest LCOE under its existing conditions at -4.14 cents/kWh. By applying New Jersey conditions to other states, LCOE in those states would also drop significantly as shown in Table 2. These results indicate that the LCOE is very sensitive to the generous incentive of $0.248/kWh under New Jersey conditions. The negative figures illustrate that the value after tax cash flows is significantly higher than the initial investment in each state.

ENERGY PAYBACK TIME (EPBT)

CED is compared to the net AC electricity generated by solar PV systems to determine EPBT. EPBT is related to the geographical location, sun irradiance, and cell efficiency. Table 3 shows a range of EPBT for the five states of interest based on different CED values reported in [59]. EPBT for states with higher sun irradiance (CA and TX), is in the range of 1.2 to 1.4 years, while for the northern states (IN and NJ) it is approximately 30% longer in the range of 1.6 to 1.7 years. California's EPBT is the shortest because of its highest annual energy generation through solar PV systems, followed by Texas, Florida, Indiana, and New Jersey.

TABLE 2. LCOE and Economic Payback Period under a variety of financial conditions for each state

LCOE (cents/kWh)			**State | Ave. Elec. Escalation Rate (%/yr)**	**Economic Payback (yr)**	
Existing Cond.	*No Policies*	*NJ Cond.*		*Existing Cond.*	*NJ Cond.*
1.07	6.49	-5.97	CA | 2.2	3.7	1.9
5.14	8.29	-5.03	FL | 2.5	14.8	2.6
5.23	8.69	-4.57	IN | 2.1	10.8	2.7
-4.14	12.09	-4.14	NJ | 1.4	3.0	3.0
3.23	8.34	-6.21	TX | 1.1	4.9	2

TABLE 3. CED and EPBT information for the states of interest

CED (kWh/m^2)			**State**	**EPBT (year)**		
Min	*Ave*	*Max*		*Min*	*Ave*	*Max*
240	645	1600	CA	0.48	1.29	3.19
			FL	0.56	1.50	3.72
			IN	0.60	1.61	4.00
			NJ	0.62	1.66	4.11
			TX	0.51	1.37	3.40

These results are consistent with what is reported by other researchers who considered SunPower module products for a utility size plant with a generation capacity of 579 MW [36].

PRICE PER UNIT MASS OF CO_2 EQUIVALENT ABATEMENT

All states show a positive price of CO_2 equivalent abatement, as shown in Table 4 (existing conditions). Losses or profits can be determined by negative or positive price of CO_2 equivalent abated, respectively. As expected, the states with better financial incentives that result in higher NPV (CA and NJ) perform better than the others. It is interesting to note that while New Jersey appears to have the highest incentives and policies among all the states [40], California still outperforms New Jersey at $151 to $93 per metric ton of CO_2 equivalent abatement price, due to higher NPV of the developing solar PV systems for manufacturing facilities in CA. This favorable price results from better weather conditions for solar energy generation and higher savings in electricity bills in CA. The two most dominant factors on price of CO_2 equivalent abatement are: 1) available financial incentives/regulatory policies and 2) solar PV system electricity generation. Florida has the lowest dollar amount of lower than $1 per ton of CO_2 equivalent abatement followed by Indiana at $14. For instance, if net metering is not available in the selected states, the price would drop to lower than zero for all the states except New Jersey. Detail information for the price of CO_2 equivalent abatement are presented in Table 4. These variations in the price of CO_2 equivalent abatement confirms the results reported by McKinsey [62].

CUMULATIVE AIR EMISSION BENEFITS

Cumulative emission avoided during the 25-year duration of the study is calculated based on the amount of energy generated by the solar PV system including degradation and the emission of eGRID sub-regions in which the selected

TABLE 4. Price per metric ton of CO_2 eq. abatement under different conditions for each state

	Abatement Cost of CO_2 Equivalent ($/Mt of CO_2 eq.)			
State	*Existing Cond.*	*No Policies*	*Incentives*	*Regulatory Policies*
CA	151.30	-109.47	-18.14	59.97
FL	0.53	-72.90	-45.20	-27.17
IN	14.21	-61.99	-37.36	-10.42
NJ	92.99	-141.70	-48.41	-97.13
TX	41.88	-73.43	-28.45	-3.11

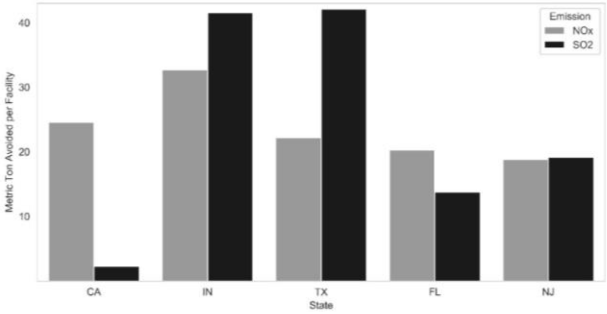

Figure 3: Cumulative avoided air emissions in five states if using 1.75-MW roof-mounted solar PV systems to power manufacturing facilities. Indiana and Texas show largest gains in emission reductions from using solar energy. In California and Florida, the highest avoided emission is NO_x while it is SO_2 in the other states.

states are located. The emissions considered in this section include NO_x and SO_2. Fig. 3, presents the cumulative avoided amount of each emission by using 1.75-MW solar PV systems to power manufacturing facilities in each state. Among the five states, Indiana shows the largest gain in the amount of avoided NO_x at 32.72 metric ton, followed by California at 24.58 metric ton. Texas benefits the most by avoidance of 42.10 metric tons of SO_2 followed by Indiana at 41.52 metric tons. Battery manufacturers in Florida could reduce NO_x and SO_2 emissions by 20.28 and 13.79 metric ton, respectively, while New Jersey could reduce these emissions by 18.82 and 19.19 metric ton, respectively. In contrast, a manufacturer in California could avoid SO_2 emission by only 2.25 metric ton.

V. DISCUSSION AND CONCLUSION

Effective, strategic and strong long-term regulatory policies such as permits, net metering, interconnection, RPS, FiT and financial incentives like production-based incentives, and tax credit could directly or indirectly support the widespread adoption of PV systems for roof-top solar applications in manufacturing facilities. The results indicate that deployment of solar energy for the industrial sector not only can become environmentally advantageous but also economically attractive for the investors such as U.S. iron and steel sector [63]. This study shows that when there are no financial incentives or regulatory policies available, none of the states can payback the investment over the 25-year period of study. When states have only regulatory policies in effect (without financial incentives), net metering is the most significant policy (which was in effect in 73% of the cases explored by [64]), facilities in four out of five states (CA, FL, IN, TX) can achieve payback on the investment within 25 years. When considering only financial incentives, only facilities in New Jersey can achieve economic payback on the investment due to the higher cash incentives. When both financial incentives and regulatory policies are imposed at the same time, all the states can achieve payback on the investment within the 25-year period. The results of this study indicate that net metering together with direct cash programs like production-based incentives play significant roles in the economic feasibility of the solar project and can be more effective than other incentives such as tax credits. Results are consistent with other research findings with regard to the effectiveness of incentives and policies provided to promote solar energy [64, 65]. Other economic factors were determined LCOE and NPV, and then used to calculate the price of CO_2 equivalent abatement per unit mass. The LCOE can be used as a metric to assess the profitability of the investment in renewable technologies. A comparison of the LCOE to the market price/regional cost of energy for the states of interest, which reported in the Appendix A, illustrates that the LCOE for a solar PV system is lower than the regional cost of energy under the existing incentives and policies for the selected states except Florida.

From environmental impact analysis point of view, life cycle CED of solar PV panels is used to determine EPBT for each state. Surprisingly, all the states considered in this study, can provide EPBT of less than two years if the average value of CED for monocrystalline silicon is considered [59]. Additionally, cumulative reduction of nitrogen oxide (NO_x), sulfur dioxide (SO_2) are assessed for each state according to eGRID sub-region database [61]. The environmental analysis shows that Indiana could achieve the highest reduction of NO_x. The highest gain of CO_2 equivalent abatement per metric ton belongs to California at $151 followed by New Jersey at $93, due to their progressive financial incentives. The current carbon credits range from $2 to $14 per ton, are provided under the common operating emissions systems Regional Greenhouse Gas Initiative (RGGI) that has nine-member states and the California system. These carbon credits are not sufficient to impact reduction in economic payback time or LCOE. If higher emission credits become available in the future, the investment and energy generation through solar PV systems could increase in appeal to the manufacturing sector [66, 67].

Improving the impact of dollars spent is the objective of policy makers when providing policies and incentives for renewable energies which could be investigated in the future studies. The potential of developing a solar plant utilizing different types of solar modules (e.g., InGaP, InGa, CdTe and multi-crystalline) different efficiencies and consideration of energy storage systems could be investigated to determine enhancements to the environmental and economic tradeoffs. Storage systems have significant impacts on the economic and environmental feasibility of renewable energy technology investments; therefore, selecting a proper size storage system plays a crucial role. Reports illustrated that the storage capacity has a significant impact on economic payback period and required to be carefully sized or just utilized a PV system without storage [66]. Another study discussed that the roof-mounted solar PVs with storage systems are not feasible in locations with low solar insolation although they could be suitable for other locations [68]. Finally, a few scenarios of electricity generation through renewable sources by considering an integrated intelligent storage and renewable energy generation systems which allow “auto-production” and “self-consumption” of electricity are evaluated [69].

The insights from this study are helpful for manufacturer and policy makers to evaluate renewable PVs as a potential source of energy for manufacturing facilities. Although each manufacturing facility is different, roof-mounted solar PV systems show high potential in economic feasibility for locations that are not always obvious sunny locales. The analysis provides economic and environmental outcomes of different financial incentive and regulation scenarios for manufacturers in five states to distinguish among the renewable energy policies to enable viable onsite electricity generation.

Appendix A. Information on the cost parameters of the solar PV system

Main cost parameter assumption	States	Value	Source
PV module cost	All states	0.47 $/Wdc	[70, 71]
Inverter	All states	4,500 $/unit	[72]
BOS equipment	CA	0.24 $/Wdc	[70]
	FL	0.36 $/Wdc	[70]
	IN	0.26 $/Wdc	[70]
	NJ	0.30 $/Wdc	[70]
	TX	0.27 $/Wdc	[70]
Installation Labor	CA	0.16 $/Wdc	[70]
	FL	0.11 $/Wdc	[70]
	IN	0.16 $/Wdc	[70]
	NJ	0.17 $/Wdc	[70]
	TX	0.11 $/Wdc	[70]
Installer overhead	CA	0.18 $/Wdc	[70]
	FL	0.15 $/Wdc	[70]
	IN	0.16 $/Wdc	[70]
	NJ	0.17 $/Wdc	[70]
	TX	0.14 $/Wdc	[70]
Permitting	All states	0.10 $/Wdc	[70]
Fixed O&M	All states	17 ± 10 $/kW/yr	[73]
Engineering overhead	CA	0.35 $/Wdc	[70]
	FL	0.35 $/Wdc	[70]
	IN	0.36 $/Wdc	[70]
	NJ	0.37 $/Wdc	[70]
	TX	0.33 $/Wdc	[70]
Electricity cost	CA	TOU (0.08-0.15 $/kWh)	[74]
	FL	0.04 $/kWh	[74]
	IN	0.06 $/kWh	[74]
	NJ	0.03 $/kWh	[74]
	TX	0.07 $/kWh	[74]
Federal income tax rate	All states	21%	[75]
State income tax rate	CA	8.84%	[76]
	FL	5.50%	[76]
	IN	6.00%	[76]
	NJ	9.00%	[76]
	TX	0.00%	[76]
Sales tax	CA	8.54%	[76]
	FL	6.00%	[76]
	IN	7.00%	[76]
	NJ	6.87%	[76]
	TX	8.17%	[76]
Property tax rate	CA	0.74% / yr	[77]
	FL	1.00% / yr	[77]
	IN	0.85% / yr	[77]
	NJ	2.40% / yr	[77]
	TX	1.81% / yr	[77]
Insurance rate	All states	0.5% of installed cost/yr	[78]
Contingency	CA	5%	[70]
	FL	5%	[70]
	IN	5%	[70]
	NJ	5%	[70]
	TX	4%	[70]
Real discount rate	All states	5% /yr	Assumed
Inflation rate	All states	2.5% /yr	Assumed

Appendix B. State level business incentives and solar policy information

	California	Florida	Indiana	New Jersey	Texas	Source
Population [Million]	39.6	21	6.7	9.006	28.3	[79]
GDP from mfg [Billion $]	305	48	106	41	246	[42]
% of total state products from mfg	11.1%	5%	29.5%	8.5%	14.5%	[42]
No. of mfg firms	36117	12367	7102	7100	17594	[42]
No. of mfg employees [x 1000]	1284	345	517	241	848	[42]
Business Tax climate index ranking	48	4	9	50	13	[80]
Corporate Tax ranking	32	19	23	42	49	[80]
Cost of doing business ranking	49	31	1	43	21	[81]
Eco-friendly behavior ranking	4	26	42	13	37	[82]

Overall solar grade	B	C	C	A	C	[40, 41]
RPS grade (renewable portfolio standards)	A	F	D	B	D	[40, 41]
Net metering grade	A	A	B	A	D	[40, 41]
Net metering value	Monthly total excess credited to next month bill in $ at sell rates					[40]
Interconnection grade	A	D	B	A	D	[40, 41]
Interconnection value	$800	$5,000	$5,000	$5,000	$500	[40]
Tax credit grade	F	C	F	F	C	[40, 41]
Investment tax credit (Federal)	30%	30%	30%	30%	30%	[40]
Property tax exemption grade	A	A	A	A	A	[40, 41]
Performance payment grade	D	D	D	A	F	[40, 41]
Production based incentive ($/kWh)	0.0612 (for 10 years)	0	0	0.248 (for 10 years)	0	[40]
Capacity based incentive	0	0	0	0	583 $/kW ac + 0.2519 $/kWh ac	[40]

REFERENCES

1. Agency, I.E., *Key world energy statistics*. 2017, International Energy Agency: International Energy Agency.
2. Allen, M.R., et al., *IPCC fifth assessment synthesis report-climate change 2014 synthesis report*. 2014.
3. Cerdas, F., et al., *Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System*. Journal of Industrial Ecology, 2017. **21**(S1).
4. WorldBank, T.W.B. *Manufacturing, value added to % of GDP*. 2017; Available from: https://data.worldbank.org/indicator/NV.IND.MANF.ZS?view=chart.
5. BEA, *Gross-Domestic-Product-(GDP)-by-Industry Data*. 2018, Bureau of Economic Analysis: bea.gov.
6. Dornfeld, D.A., *Moving towards green and sustainable manufacturing*. International Journal of Precision Engineering and Manufacturing-Green Technology, 2014. **1**(1): p. 63-66.
7. IRENA, *Renewable Energy in Manufacturing*. 2014, International Renewable Energy Agency: International Renewable Energy Agency.
8. DOE. *Static Sankey Diagram Full Sector Manufacturing*. 2010; Available from: https://www.energy.gov/eere/amo/static-sankey-diagram-full-sector-manufacturing.
9. Hsueh, L. *Why IT companies lead on proactive climate action*. 2015; Available from: https://www.brookings.edu/blog/techtank/2015/12/01/why-it-companies-lead-on-proactive-climate-action/.
10. EPA. *Local Renewable Energy Benefits and Resources*. 2018; Available from: https://www.epa.gov/statelocalenergy/local-renewable-energy-benefits-and-resources.
11. Polaris. *5 Reasons to Consider On-Site Power Generation*. 2014; Available from: http://www.polarisengr.com/engineering/5-reasons-consider-on-site-power-generation/.
12. Penndorf, S., *An Introduction to Renewable Energy Procurement: Onsite Solar Generation*. 2016, 3Degrees: 3degreesinc.com.
13. Weisser, D., *A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies*. Energy, 2007. **32**(9): p. 1543-1559.
14. Pryor, S.C. and R.J. Barthelmie, *Climate change impacts on wind energy: A review*. Renewable and Sustainable Energy Reviews, 2010. **14**(1): p. 430-437.
15. Trancik, J.E., et al., *Technology improvement and emissions reductions as mutually reinforcing efforts: Observations from the global development of solar and wind energy*. 2015, MIT.
16. Jacobson, M.Z., *Review of solutions to global warming, air pollution, and energy security*. Energy & Environmental Science, 2009. **2**(2): p. 148-173.
17. LAZARD, *Lazard's Levelized Cost of Energy Analysis*. 2017, LAZARD: lazard.com.
18. Roddis, P., et al., *The role of community acceptance in planning outcomes for onshore wind and solar farms: An energy justice analysis*. Applied Energy, 2018. **226**: p. 353-364.
19. Roselund, C., *Big steel goes big solar*, in *pv magazine*. 2018, pv magazine: https://pv-magazine-usa.com/.
20. TESLA. *Tesla Gigafactory*. 2018; Available from: https://www.tesla.com/gigafactory.
21. Fais, B., N. Sabio, and N. Strachan, *The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and*

renewable targets. Applied Energy, 2016. **162**: p. 699-712.
22. Karali, N., *Industrial sector energy efficiency modeling (ISEEM) framework documentation.* 2012.
23. EIA, *Energy Consumption Overview: Estimates by Energy Source and End-Use Sector*. 2018, U. S. Energy Information Administration: eia.gov.
24. EPA, *Sources of Greenhouse Gas Emissions*. 2018, EPA: epa.gov.
25. Hakimian, A., et al., *Economic analysis of CNT lithium-ion battery manufacturing.* Environmental Science: Nano, 2015. **2**(5): p. 463-476.
26. EIA, *MANUFACTURING ENERGY CONSUMPTION SURVEY (MECS)*. 2014, EIA: https://www.eia.gov/consumption/manufacturing/data/2014/.
27. SunPower. *X-Series Commercial Solar Panels*. 2017; Available from: https://us.sunpower.com/sites/sunpower/files/uploads/resources/sp-x21-470-460-445-ds-en-ltr-mc4comp-524935-0.pdf.
28. NREL, *National Solar Radiation Database*. 2014, National Renewable Energy Laboratory: nrel.gov.
29. Aldrich, B., et al., *Style Manual: Third Edition*. 2015, California Energy Commission: energy.ca.gov. p. 1-96.
30. NREL, *System Advisor Model (SAM)*. 2016, National Renewable Energy Laboratory: sam.nrel.gov.
31. NREL, *Direct Normal Solar Irradiance*. 2016, National Renewable Energy Laboratory: nrel.gov.
32. Ito, M., et al., *A comparative study on cost and life‐cycle analysis for 100 MW very large‐scale PV (VLS‐PV) systems in deserts using m‐Si, a‐Si, CdTe, and CIS modules.* Progress in Photovoltaics: Research and Applications, 2008. **16**(1): p. 17-30.
33. NREL, *Photovoltaic Degradation Rates — An Analytical Review*. 2012, NREL: https://www.nrel.gov/docs/fy12osti/51664.pdf.
34. Gul, M., Y. Kotak, and T. Muneer, *Review on recent trend of solar photovoltaic technology.* Energy Exploration & Exploitation, 2016. **34**(4): p. 485-526.
35. de Wild-Scholten, M.J., *Energy payback time and carbon footprint of commercial photovoltaic systems.* Solar Energy Materials and Solar Cells, 2013. **119**: p. 296-305.
36. Francke, L., et al. *GHG Emissions and Energy Payback Time of AC electricity generated by the SunPower® Oasis® photovoltaic power plant*. in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*. 2015.
37. Lazaroiu, G.C., et al., *Comparative analysis of fixed and sun tracking low power PV systems considering energy consumption.* Energy Conversion and Management, 2015. **92**: p. 143-148.
38. Al-Mohamad, A., *Efficiency improvements of photo-voltaic panels using a Sun-tracking system.* Applied Energy, 2004. **79**(3): p. 345-354.
39. EIA. *ELECTRICITY DATA BROWSER*. 2018; Available from: https://www.eia.gov/electricity/data/browser/.
40. DSIRE. *Database of State Incentives for Renewables & Efficiency*. 2018; Available from: http://programs.dsireusa.org/.
41. Wavesolar. *2018 State Solar Power Rankings Report*. 2018; Available from: https://solarpowerrocks.com/2018-state-solar-power-rankings/.
42. NAM. *State Manufacturing Data*. 2018 [cited 2018; Available from: http://www.nam.org/Data-and-Reports/State-Manufacturing-Data/.
43. Rahmandad, H. and J.D. Sterman, *Reporting guidelines for simulation-based research in social sciences.* System Dynamics Review, 2012. **28**(4): p. 396-411.
44. Schulze, M., S. Heidenreich, and P. Spieth, *The Impact of Energy Management Control Systems on Energy Efficiency in the German Manufacturing Industry.* Journal of Industrial Ecology, 2018. **22**(4): p. 813-826.
45. Peng, J., L. Lu, and H. Yang, *Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems.* Renewable and Sustainable Energy Reviews, 2013. **19**: p. 255-274.
46. Armendariz-Lopez, J.F., et al., *Energy payback time and Greenhouse Gas emissions: Studying the international energy agency guidelines architecture.* Journal of Cleaner Production, 2018. **196**: p. 1566-1575.
47. Collins, K., B. Powell, and A. Anctil. *Life cycle assessment of silicon solar panels manufacturing in the United States*. in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*. 2015.
48. Yue, D., F. You, and S.B. Darling, *Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis.* Solar Energy, 2014. **105**: p. 669-678.
49. Mason, J., et al., *Energy payback and life‐cycle CO2 emissions of the BOS in an optimized 3・5 MW PV installation.* Progress in Photovoltaics: Research and Applications, 2006. **14**(2): p. 179-190.
50. Murphy, F. and K. McDonnell, *A Feasibility Assessment of Photovoltaic Power Systems in Ireland; a Case Study for the Dublin Region.* Sustainability, 2017. **9**(2): p. 302.
51. Sherwani, A.F., J.A. Usmani, and Varun, *Life cycle assessment of solar PV based electricity generation systems: A review.* Renewable and Sustainable Energy Reviews, 2010. **14**(1): p. 540-544.

52. Kato, K., A. Murata, and K. Sakuta, *An evaluation on the life cycle of photovoltaic energy system considering production energy of off-grade silicon.* Solar Energy Materials and Solar Cells, 1997. **47**(1): p. 95-100.
53. Jungbluth, N., M. Tuchschmid, and M. de Wild-Scholten, *Life Cycle Assessment of Photovoltaics: update of ecoinvent data V2. 0.* ESU-services Ltd, 2008.
54. Fthenakis, V. and E. Alsema, *Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004–early 2005 status.* Progress in photovoltaics: research and applications, 2006. **14**(3): p. 275-280.
55. Alsema, E., M. de Wild-Scholten, and V. Fthenakis. *Environmental impacts of PV electricity generation-a critical comparison of energy supply options*. in *21st European photovoltaic solar energy conference*. 2006.
56. Alsema, E. and M.J. de Wild, *Environmental impact of crystalline silicon photovoltaic module production.* MRS Online Proceedings Library Archive, 2005. **895**.
57. de Wild-Scholten, M. *Energierücklaufzeiten für PV-module und systeme energy payback times of PV modules and systems*. in *Workshop Photovoltaik-Modultechnik*. 2009.
58. Todde, G., et al., *Embodied Energy and Environmental Impact of Large-Power Stand-Alone Photovoltaic Irrigation Systems.* Energies, 2018. **11**(8): p. 2110.
59. Zhou, Z. and M. Carbajales-Dale, *Assessing the photovoltaic technology landscape: efficiency and energy return on investment (EROI).* Energy & Environmental Science, 2018. **11**(3): p. 603-608.
60. Koppelaar, R.H.E.M., *Solar-PV energy payback and net energy: Meta-assessment of study quality, reproducibility, and results harmonization.* Renewable and Sustainable Energy Reviews, 2017. **72**: p. 1241-1255.
61. EPA, *Emissions & Generation Resource Integrated Database (eGRID)*. 2016: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid.
62. Nauclér, T. and P.-A. Enkvist, *Pathways to a low-carbon economy: Version 2 of the global greenhouse gas abatement cost curve.* McKinsey & Company, 2009. **192**.
63. Karali, N., W.Y. Park, and M. McNeil, *Modeling technological change and its impact on energy savings in the U.S. iron and steel sector.* Applied Energy, 2017. **202**: p. 447-458.
64. Matisoff, D.C. and E.P. Johnson, *The comparative effectiveness of residential solar incentives.* Energy Policy, 2017. **108**: p. 44-54.
65. Mormann, F., *Enhancing the investor appeal of renewable energy*. Environmental law, 2012: p. 681-734.
66. Zhang, J., et al., *Integrated photovoltaic and battery energy storage (PV-BES) systems: An analysis of existing financial incentive policies in the US.* Applied Energy, 2018. **212**: p. 895-908.
67. Gibbs, J.S.Z.K.H.T.S., *Carbon Markets: Renewed Expectations*. 2015, Institute of International Finanace: IIF. p. 1-7.
68. Nicholls, A., R. Sharma, and T.K. Saha, *Financial and environmental analysis of rooftop photovoltaic installations with battery storage in Australia.* Applied Energy, 2015. **159**: p. 252-264.
69. Germani, M., D. Landi, and M. Rossi, *Efficiency and Environmental Analysis of a System for Renewable Electricity Generation and Electrochemical Storage of Residential Buildings.* Procedia CIRP, 2015. **29**: p. 839-844.
70. Fu, R., D. Feldman, and R. Margolis, *U.S. Solar Photovoltaic System Cost Benckmark: Q1 2018*. 2018, National Renewable Energy Laboratory: nrel.gov.
71. PVinsights. *PVinsights*. 2018 [cited 2017 May 20]; Available from: http://pvinsights.com/.
72. ABB, *Solar Inverter*, ABB, Editor. 2014, Solaris.
73. Walker, A., *PV O&M cost model and cost reduction*. 2017, National Renewable Energy Lab.(NREL), Golden, CO (United States).
74. URDB. *Electric Utility Rates*. 2018; Available from: https://openei.org/wiki/Utility_Rate_Database.
75. Pomerleau, K. *The United States' Corporate Income Tax Rate is Now More in Line with Those Levied by Other Major Nations*. 2018; Available from: https://taxfoundation.org/us-corporate-income-tax-more-competitive/.
76. Jared, W.S., Drenkard. *State and Local Sales Tax Rates 2018*. 2018; Available from: https://taxfoundation.org/state-and-local-sales-tax-rates-2018/.
77. Kiernan, J.S. *2018's Property Taxes by State*. 2018; Available from: https://wallethub.com/edu/states-with-the-highest-and-lowest-property-taxes/11585/.
78. Speer, B., M. Mendelsohn, and K.S. Cory, *Insuring solar photovoltaics: Challenges and possible solutions*. 2010: National Renewable Energy Laboratory.
79. Census-Bureau. *State Population Totals*. 2018; Available from: https://www.census.gov/data/datasets/2017/demo/popest/state-total.html#par_textimage_500989927.
80. TAX-FOUNDATION. *2018 State Business Tax Climate Index*. 2018; Available from: https://taxfoundation.org/publications/state-business-tax-climate-index/.
81. Cohn, S. *America's Top States for Business*. 2015 24-June-2015 [cited 2015; Available from: https://www.cnbc.com/2015/06/24/00-advantages-minnesota-is-2015s-top-state.html.
82. Kiernan, J.S. *2018's Greenest States*. 2018; Available from: https://wallethub.com/edu/greenest-states/11987/.