


Article

Quantifying the Techno-Economic Potential of Grid-Tied Rooftop Solar Photovoltaics in the Philippine Industrial Sector [†]

Patrick Gregory B. Jara ^{1,2}, Michael T. Castro ¹, Eugene A. Esparcia, Jr. ¹  and Joey D. Ocon ^{1,*}

¹ Laboratory of Electrochemical Engineering (LEE), Department of Chemical Engineering, University of the Philippines Diliman, Quezon City 1101, Philippines; pgbjara@meralco.com.ph (P.G.B.J.); mtcastro1@up.edu.ph (M.T.C.); eaesparcia@upd.edu.ph (E.A.E.J.)

² Manila Electric Company (MERALCO), Pasig City 1604, Philippines

* Correspondence: jdocon@up.edu.ph

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Abstract: The industrial sector is a major contributor to the economic growth of the Philippines. However, it is also one of the top consumers of energy, which is produced mainly from fossil fuels. The Philippine industrial sector must therefore be supported economically while minimizing the emissions associated with energy consumption. A potential strategy for minimizing costs and emissions is the installation of solar photovoltaic (PV) modules on the rooftops of industrial facilities, but this approach is hindered by existing energy policies in the country. In this work, we performed a techno-economic assessment on the implementation of rooftop solar PV in Philippine industrial facilities under different policy scenarios. Our study considered 139 randomly sampled industrial plants under MERALCO franchise area in the Philippines. Under the current net metering policy, 132 of the evaluated facilities were economically viable for the integration of rooftop solar PV. This corresponds to an additional 1035 MW_p of solar PV capacity and the avoidance of 8.4 million tons of CO₂ emissions with minimal financial risk. In comparison, an expanded net metering policy supports the deployment of 4653 MW_p of solar PV and the avoidance of 38 million tons of CO₂. By enabling an enhanced net metering policy, the widespread application of rooftop solar PV may present considerable savings and emission reduction for energy-intensive industries (electrical and semiconductors, cement and concrete, steel and metals, and textile and garments) and lower generation costs for less energy intensive industries (construction and construction materials, transportation and logistics, and food and beverages).

Keywords: rooftop solar PV; net metering; Philippines; industrial sector

1. Introduction

The Philippine industrial sector contributed to around 35% of the country's gross domestic product in 2019 [1]. Unfortunately, its development is hampered by the high cost of electricity (~USD 0.19/kWh), which ranks as the second highest in Asia [2]. In addition, the large energy consumption of the industrial sector is met with environmental pressure due to the CO₂ emissions associated with the country's energy mix. To solve these problems, the implementation of rooftop solar photovoltaic (PV) on industrial facilities has been investigated due to the ample solar energy potential in the

Philippines [3]. The displacement of energy from the grid by solar PV generation can reduce emissions, while selling excess solar PV generation to the grid via net metering may yield profits [4]. Typically, these systems show a payback period (PBP) from 3 to 11 years and an internal rate of return (IRR) between 21% to 29% [5–8]. Furthermore, the feasibility of simultaneous heating and energy generation from solar PV has been demonstrated in other countries [9].

The cost savings and environmental benefits are not the only important factors. The widespread deployment of rooftop solar PV is heavily dependent on regulatory policies. One of the enabling support frameworks is net metering policy, which allows consumers to be prosumers by selling excess generation to the grid [10]. In the Philippines, this is promulgated by the Renewable Energy Act of 2008 and implemented through Energy Regulatory Commission (ERC) Resolution 9 Series of 2013. This scheme compensates exported electricity at a rate equal to the average monthly blended generation rate, but is applicable only for exports below 100 kW [11]. Thus, this policy benefits residential consumers in the Philippines [12] but provides limited opportunities for the industrial sector [13]. A study by Ghosh and co-workers demonstrated that increasing the export limit to 5 MW_p in Bangalore, India can improve the economic viability of integrating solar PV systems into their industrial sector [7]. Enabling an expanded net metering policy in the Philippines may likewise promote the widespread adoption of solar PV by the country's industrial sector [14].

In a prior study, we demonstrated that the implementation of rooftop solar PV in some Philippine sub-industries (Electrical and Semiconductors, Steel and Metals, Food and Beverages, Transportation and Logistics, and Textile and Garments) generated additional energy supply and cost savings, especially if the export limit is amended [15]. In this work, we extend our initial study by including more sub-industries to create a more comprehensive outlook on the viability of rooftop solar PV deployment. This work adopts the four-part analysis employed in our previous work. First, the feasibility of rooftop solar PV installations under the existing net metering policy was determined. Second, expanded scenarios were formed based on possible policy interventions. Third, a techno-economic optimization was performed on solar rooftop installations under the enhanced scenarios. Lastly, the rooftop solar PV installations on industrial plants were assessed based on economic metrics and the possibility for grid defection as demand-side management. This work equips various stakeholders with crucial quantitative information on the potential of rooftop solar PV, the associated economic benefits, and the reduction in CO₂ emissions.

2. Materials and Methods

2.1. General Approach

This study will follow the same general approach used in our previous work [15]. This includes the scenarios of rooftop solar PV implementation, shown in Table 1, which are based on current and proposed policies in the Philippines.

The energy system in the Base Scenario, Improved Policy, and Max Roof Capacity scenarios are illustrated in Figure 1, while that of the Off-Grid scenario is depicted in Figure 2. The off-grid operation of an industrial facility is currently discouraged by the present economic outlook [16] but this scenario is described by the Interruptible Load Program (ILP) of the Philippine government. When the country's energy supply is insufficient, especially during the summer period, the ILP encourages industrial facilities to disconnect from the main grid and operate in islanded mode [17].

Table 1. Energy policy scenarios considered in this work.

Scenario	Description
Base Scenario	<ul style="list-style-type: none"> • Solar PV + grid system • 100 kW_p solar PV export limit • Excess generation paid according to blended generation rate • Based on current net metering scheme in the Philippines

Table 1. Cont.

Scenario	Description
Improved Policy	<ul style="list-style-type: none"> • Solar PV + grid system • No solar PV export limit • Excess generation paid according to blended generation rate • Solar PV installation size is optimized to maximize the net present value (NPV)
Max Roof Capacity	<ul style="list-style-type: none"> • Solar PV + grid system • No solar PV export limit • Excess generation paid according to blended generation rate • Solar PV installation consumes the entire roof area
Off-Grid Scenario	<ul style="list-style-type: none"> • Solar PV + battery + diesel generator system • Li-ion and lead–acid batteries will be compared • Installation sizes is optimized to maximize the NPV • Based on the Interruptible Load Program (ILP)

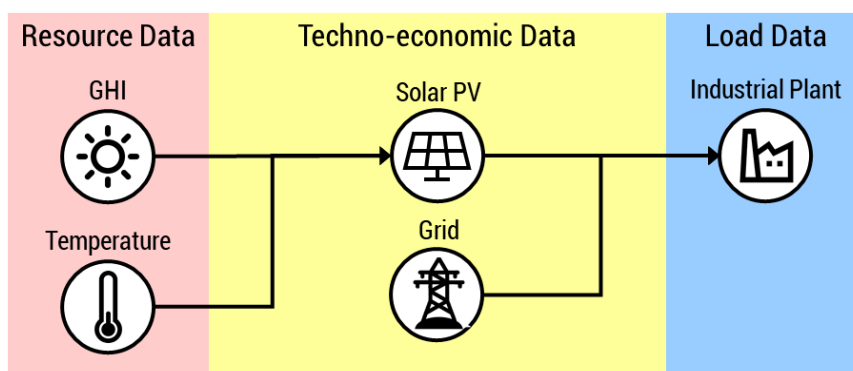


Figure 1. The industrial plant under the Base Scenario, Improved Policy, and Max Roof Capacity scenarios are powered by solar PV and the grid.

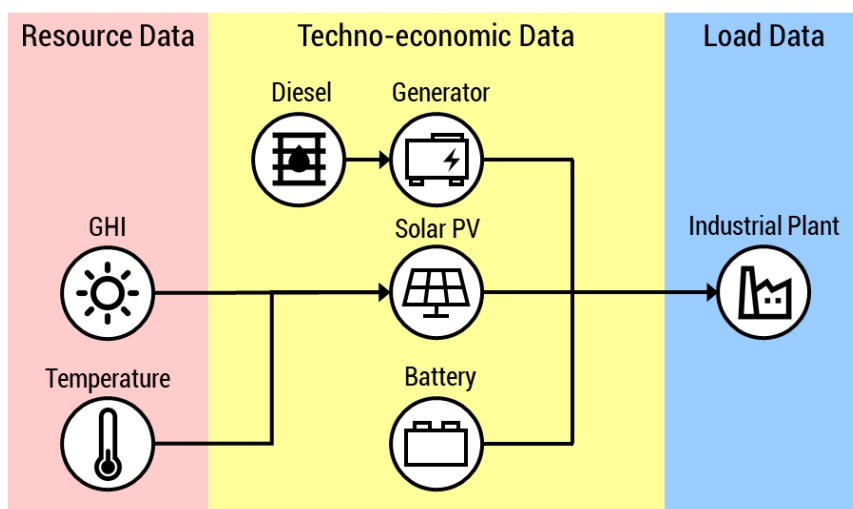


Figure 2. The industrial plant under the Off-Grid scenario is powered by solar PV, a battery (either lithium-ion or lead–acid), and a diesel generator.

2.2. Philippine Industrial Sector Data

2.2.1. Sampling Methodology

A total of 139 randomly sampled industrial plants were considered in this study. This consists of the 66 facilities from the initial study [15] and 73 more facilities from the 13 additional sub-industries

included in this work. The samples were sourced from the 17,793 plants located at the main industrial area of the Philippines being served by Manila Electric Company (MERALCO). The random sampling methodology was comparable to that used in surveys [18]. The total sample size was computed using a 7.5% margin of error and 92.5% confidence level, which were selected based on the available resources for the study. All the selected samples were classified based on the Philippine Standard of Industry Classifications from the Philippine Statistics Authority [19]. Table 2 shows the number of samples per industry classification and initial sub-industry demand data.

Table 2. Number of samples and electricity demand per sub-industry.

Sub-Industry Classification	Count	Average Load (kW)
Industries from the initial study [15]	66	133–1727
Construction and Construction Materials	11	48
Paper and Print	9	539
Plastic	8	302
Chemicals and Pharmaceutical	8	864
Cement and Concrete	7	7530
Agricultural Products	7	320
Equipment	6	131
Packaging	5	1663
Rubber	3	90
Water Utility	3	10
Glass	2	2668
Ice and Refrigeration	2	213
Oil, Gas, and Power	2	9
Total	139	

2.2.2. Resource Data

The global horizontal irradiance and temperature data required for the simulation of solar PV modules were sourced from National Aeronautics and Space Administration (NASA) [20]. These were evaluated at the location of each industrial facility. The load profiles of the selected industries were obtained from MERALCO. The peak demand of a representative facility from each sub-industry is shown in Table 3, while the normalized hourly and monthly load profiles of these facilities are shown in Figures 3 and 4, respectively. Other technical and economic parameters used in the simulations are presented in Appendices A and B.

Table 3. Peak load from each sample sub-industry.

Label ¹	Sub-Industry Classification	Peak Load (kW)
A	Electrical and Semiconductors	1193
B	Steel and Metals	161
C	Food and Beverages	111
D	Transportation and Logistics	13
E	Textile and Garments	991
F	Construction and Cons Materials	18
G	Paper and Print	2619
H	Plastic	197
I	Chemical and Pharmaceuticals	2487
J	Cement and Concrete	37,511
K	Agricultural Products	2
L	Equipment	639
M	Packaging	285
N	Rubber	15
O	Water Utility	4
P	Glass	5406
Q	Ice and Refrigeration	255
R	Oil, Gas, and Power	9

¹ These labels are used in Figures 3 and 4.

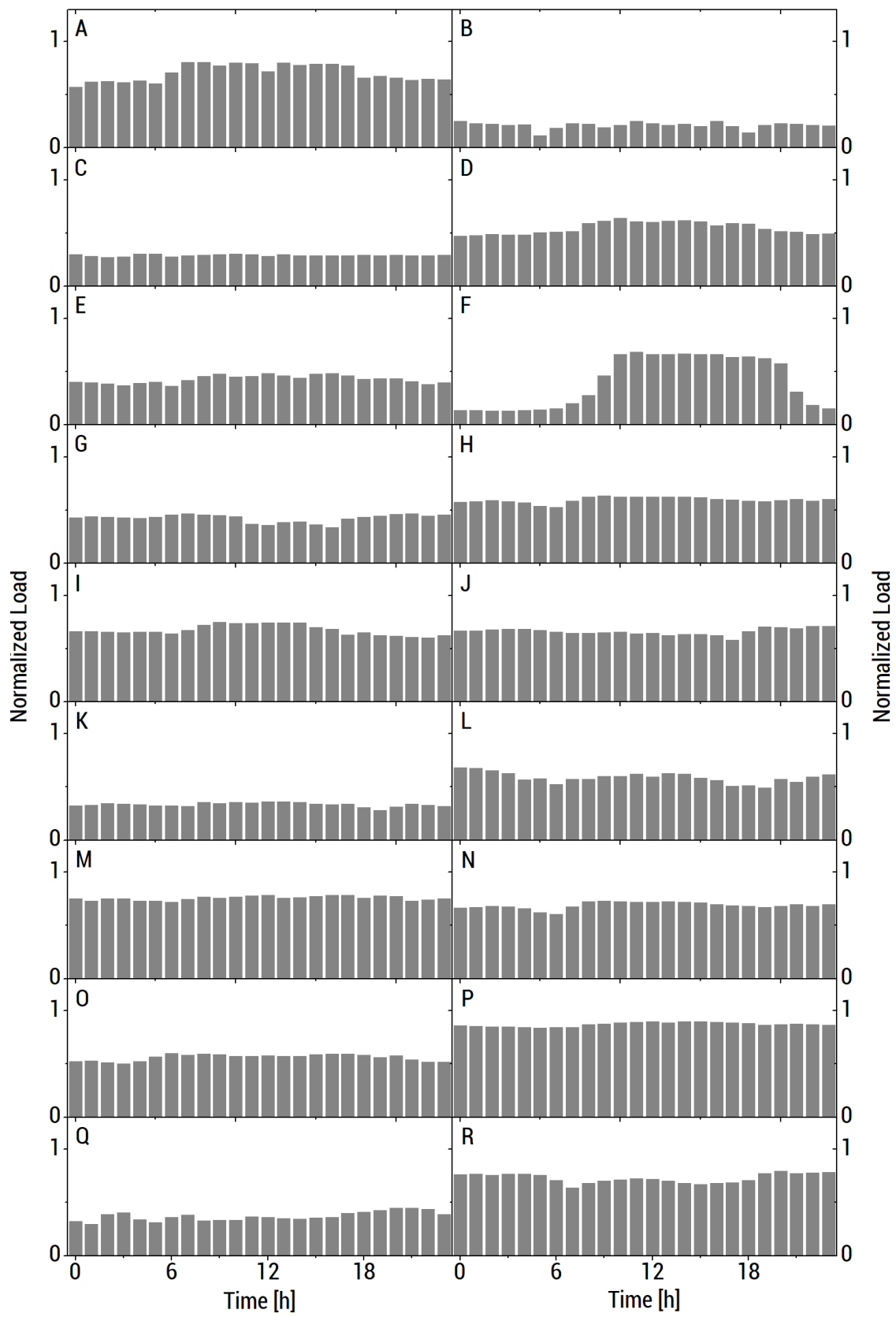


Figure 3. Hourly average of normalized load profile. The industries referred to by the labels (A–R) are given in Table 3.

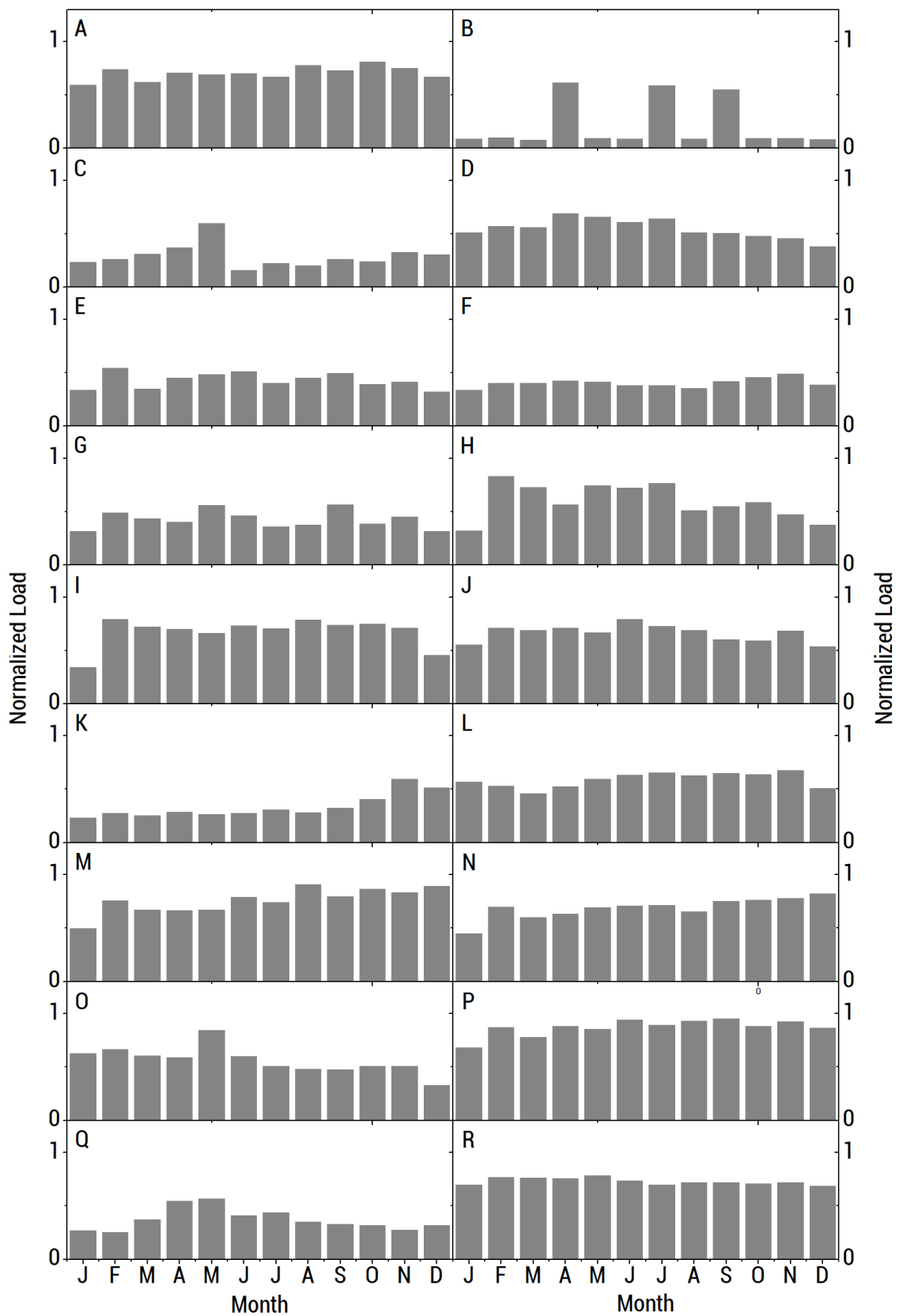


Figure 4. Monthly average of normalized load profile. The industries referred to by the labels (A–R) are given in Table 3.

2.3. ISLA Optimization Tool

The energy systems are simulated and optimized by the Island System LCOE_{min} Algorithm (ISLA), an open-source energy systems optimization tool written in Python 3. The tool was developed by our group and subsequently validated with HOMER Pro[®] [15]. The operation of the different energy components is simulated using mathematical models. The interaction of these components is then determined by the load-following dispatch algorithm, wherein generation from solar PV and the battery are prioritized and the conventional resource (grid in the Base Scenario, Improved Policy, and Max Rooftop; diesel in the Off-Grid scenario) is dispatched by just enough to meet the load. The interaction of the components is simulated for one representative year in hourly time steps. The results of the simulation are then used to determine the net present value (NPV) and other economic metrics about the system. Optimization is performed by running multiple simulations with various energy component sizes, then selecting the set of component sizes that yield the highest NPV. Details about the optimization algorithm and the mathematical models of the energy components are presented in [21].

2.4. Rooftop Potential

The solar PV installation capacity on the rooftop of each industrial facility is estimated using the procedure outlined by Kouhestani [22]. An aerial photograph of the rooftop is obtained from Google Maps[™]. The maximum solar PV potential is then calculated from the image while accounting for the rooftop construction, elevation, shading probability, and spaces for maintenance and operation workers. The solar PV panels considered in this work have a standard rating of 0.255 kW_p. Other technical details are presented in Appendix B.

2.5. Economic and Environmental Parameters

The market competitiveness of an energy system is quantified by the levelized cost of electricity (LCOE), defined as the total discounted costs of an energy system per unit of electricity generated over its lifetime [23]. It is given by Equation (1) wherein d is the discount rate, N is the project lifetime (y), $C(n)$ is the discounted cost (USD) at year n , and E_{yr} is the annual energy consumption (kWh).

$$\text{LCOE} = \frac{d(1+d)^N}{(1+d)^N - 1} \times \frac{\sum_{n=0}^N C(n)}{E_{yr}} \quad (1)$$

The NPV, IRR, and PBP determine the viability of an investment project [24]. The NPV assesses the profitability of a project and is defined as the difference between the discounted inflows and outflows. A positive value of NPV indicates a favorable investment [25]. It is given by Equation (2) wherein $R(n)$ is the discounted revenue (USD) at year n .

$$\text{NPV} = \sum_{n=0}^N \frac{R(n) - C(n)}{(1+d)^N} \quad (2)$$

The IRR compares the profitability to the discount rate. An investment is more desirable if the difference in IRR and discount rate increases [25]. It is defined as the discount rate at which the NPV is zero, as shown by Equation (3).

$$\sum_{n=0}^N [R(n) - C(n)] \times \left(\frac{1+d}{1+\text{IRR}} \right)^n = 0 \quad (3)$$

The PBP represents the number of years required to recover the investment. It is also the time when the difference between the total discounted revenue and cost is zero, as shown by Equation (4). A lower PBP indicates lower risk on a project investment [24].

$$\int_0^{\text{PBP}} \frac{R(n) - C(n)}{(1 + d)^N} = 0 \quad (4)$$

The environmental impact of the solar PV installations is also a key factor to its deployment [26]. It is quantified by the estimated reduction in CO₂ emissions of the industrial plant upon the integration of rooftop solar PV with the industrial facility's energy system. This parameter is determined from the energy supplied by the renewable energy components (solar PV and battery) and the national grid emission factor (NGEF) of the electrical grid where the MERALCO franchise area is connected to [27]. This is given by Equation (5) wherein Δm_{CO_2} is the CO₂ emission reduction (metric tons) and E_{RE} is the total energy (kWh) supplied by the renewable energy components throughout the lifecycle of the project. Note that other sources of CO₂ emissions are not considered by this metric.

$$\Delta m_{\text{CO}_2} = E_{\text{RE}} \times \text{NGEF} \quad (5)$$

3. Results and Discussion

3.1. Case Studies

In this subsection, detailed case studies are presented for two sample industrial facilities to demonstrate the application of the methodology to the industrial plants. The first case study illustrates the integration of rooftop solar PV into a grid-tied system, while the second case study shows a facility that has potential for off-grid operation.

3.1.1. Sample Cement Plant

Table 4 presents the techno-economic and environmental metrics for the sample plant while Figure 5 illustrates the rooftop utilization of solar PV under different policy scenarios.

Table 4. Techno-economic and environmental metrics describing the cement plant.

Economic Parameter	Grid	Base Scenario	Improved Policy Scenario	Max Roof Capacity Scenario	Off-Grid Scenario
LCOE (USD/kWh)	0.19	0.13	0.12	0.13	0.32
NPV (USD)	-	138,168	165,458	136,641	166,221
IRR (%)	-	7.01	7.01	0.9	-
PBP (y)	-	10.32	10.33	44.92	-
Emission reduction (tons of CO ₂)	-	81.08	97.15	348.9	-

Based on the NPV increase and CO₂ emission reduction, the results indicate that a transition from the Base Scenario to the Improved Policy scenario yields an improvement in profitability and environmental impact. The IRR and BEP are unchanged, which shows that the transition does not impose a financial risk. The application of the Max Roof Capacity scenario further decreases the CO₂ emissions but drastically reduces the economic viability of the investment. In this scenario, the savings from the rooftop solar PV installation cannot compensate for the high capital costs within a reasonable time frame. It is noteworthy that the Max Roof Capacity scenario has a lower NPV than the Base Scenario, demonstrating that maximizing the rooftop solar PV installation is not necessarily economically viable. This sample cement plant is not suitable for the Off-Grid scenario due to the high variability of the load profile and the lack of excess solar PV during daytime.

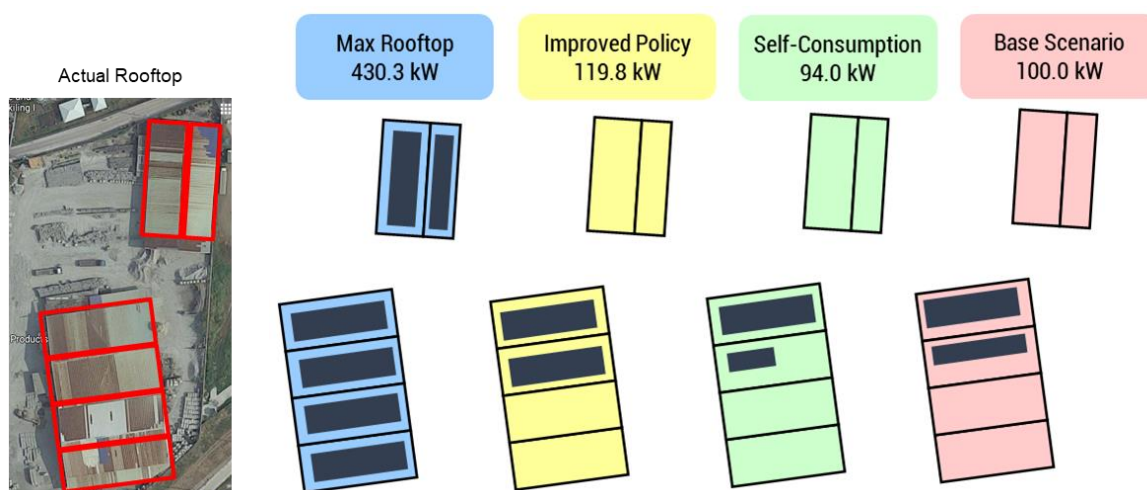


Figure 5. Illustration of the installed solar PV on the cement plant’s rooftop under each scenario.

3.1.2. Sample Transportation Facility

Table 5 presents the techno-economic and environmental metrics for the sample plant, while Figure 6 illustrates the rooftop utilization of solar PV under different policy scenarios.

Table 5. Techno-economic and environmental metrics describing the transportation facility.

Economic Parameter	Grid	Base Scenario	Improved Policy Scenario	Max Roof Capacity Scenario	Off-Grid Scenario (Lead-Acid)	Off-Grid Scenario (Lithium-Ion)
LCOE (USD/kWh)	0.19	0.17	0.13	0.13	0.33	0.33
NPV (USD)	-	136,641	425,954	425,954	681,489	666,412
IRR (%)	-	6.96	7.01	7.01	6.73	5.38
PBP (y)	-	10.44	10.31	10.31	11.03	15.14
Emission reduction (tons of CO ₂)	-	81.08	249.57	249.57	261.16	282.95

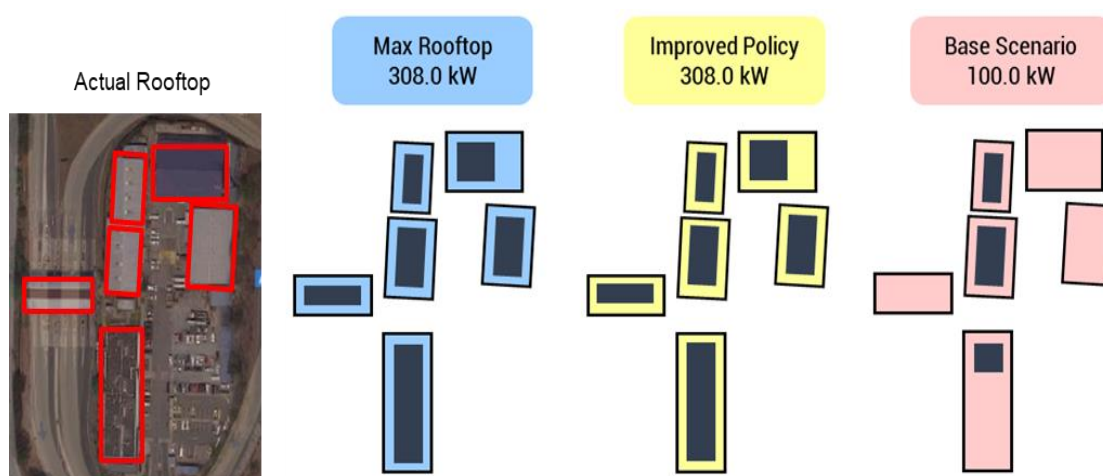


Figure 6. Illustration of the installed solar PV on the transportation facility’s rooftop under each scenario.

In this case study, the optimized solar PV sizes for both the Improved Policy and Off-Grid scenarios were equal to the maximum rooftop solar PV capacity. The expanded net metering policies clearly decreased generation costs and CO₂ emissions while improving the quality of the investment.

Furthermore, this transportation establishment is compatible with the Off-Grid scenario, so this facility can participate in the ILP.

3.2. Grid-Tied Scenario Results

Table 6 summarizes the results describing the application of the grid-tied scenarios (Base Scenario, Improved Policy, and Max Roof Capacity).

Table 6. Summary of results on the grid-tied scenarios.

Metrics	Base Scenario	Improved Policy	Max Roof Capacity
Solar PV average installed capacity (kW _p)	61.8	278	344
Solar PV total installed capacity (MW _p)	1035.0	4654	5760
LCOE (USD/kWh)	0.190	0.185	0.185
NPV (USD)	82,061	370,229	366,412
IRR (%)	7.8	7.0	7.0
PBP (y)	9.1	10.4	10.5
Average reduced CO ₂ emissions (tons of CO ₂)	50.15	226.01	279.23
Total reduced CO ₂ emissions (kilotons of CO ₂)	8412	37,984	47,327

The rooftop solar PV potential of the selected Philippine industries under the Base Scenario is 1035 MW_p, which is comparable to the installed capacity of a large conventional power plant. Of the 139 facilities analyzed, only 7 of these were unviable for rooftop solar PV installation due to shading. Incorporation of the Improved Policy scenario raises the solar PV potential to 4653 MW_p, resulting in a sharp increase in NPV and a large drop in CO₂ emissions. This strongly supports the results of our earlier work that relaxing the net metering limits can reduce electricity costs. Despite the increased savings, however, the slight reduction in IRR and PBP suggest a lower quality of investment. This is due to the high capital costs of solar PV installation. A further transition into the Max Roof Capacity scenario increases the rooftop solar potential to 5760 MW_p. This decreases the CO₂ emissions without greatly affecting the quality of investment. The NPV, however, is less than that of the Improved Policy scenario. This supports the recommendation from our previous work that optimization must be performed when implementing rooftop solar in these industrial plants.

3.3. Grid-Tied Scenario Results by Sub-Industry

3.3.1. Rooftop Solar PV Potential

Figures 7 and 8 show the average and total rooftop solar PV potential, respectively, of each sub-industry under different grid-tied scenarios.

The sub-industry analysis demonstrates that energy-intensive industries (Electrical and Semiconductors, Cement and Concrete, Packaging, and Glass) have high rooftop solar PV potentials. In addition, 61 of the 139 facilities (~44%) analyzed in this work have an optimum rooftop solar PV capacity greater than the 100 kW_p export limit. This suggests that the expansion of the current net metering policies will support the widespread deployment of rooftop solar PV. The average rooftop solar PV potential among the sampled industries is 643.2 kW_p. Raising the export limit to this value will cover majority of the scenarios during the actual implementation of rooftop solar PV in industrial plants. As for rooftop area usage, most of the sampled industries will require only 42% of their rooftop to be fitted with solar PV.

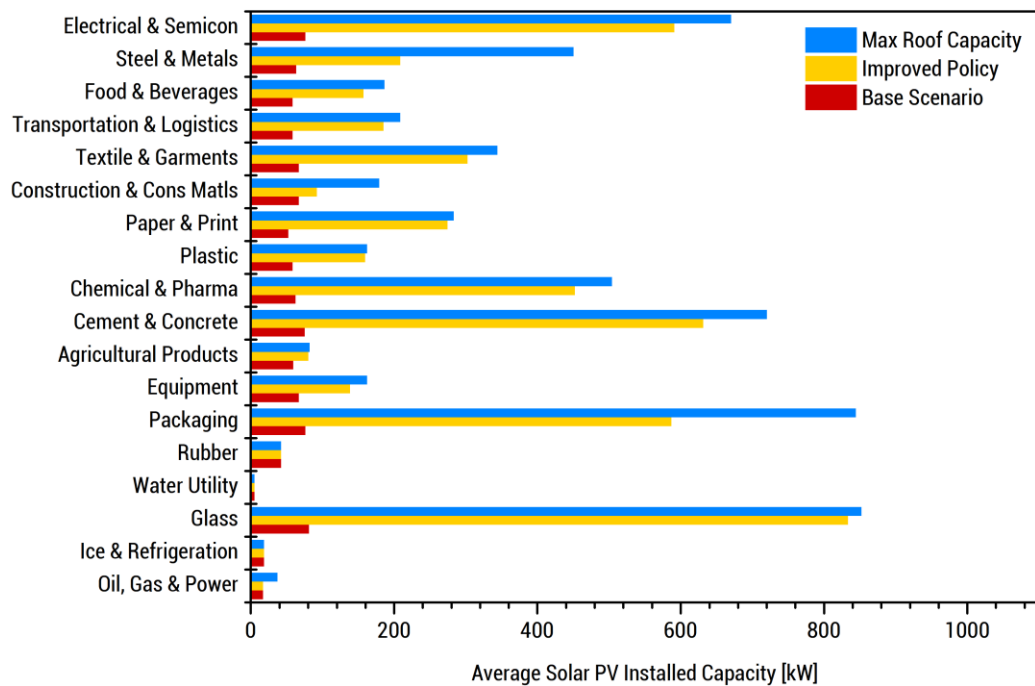


Figure 7. Average rooftop solar PV potential of the sampled industrial plants under different scenarios.

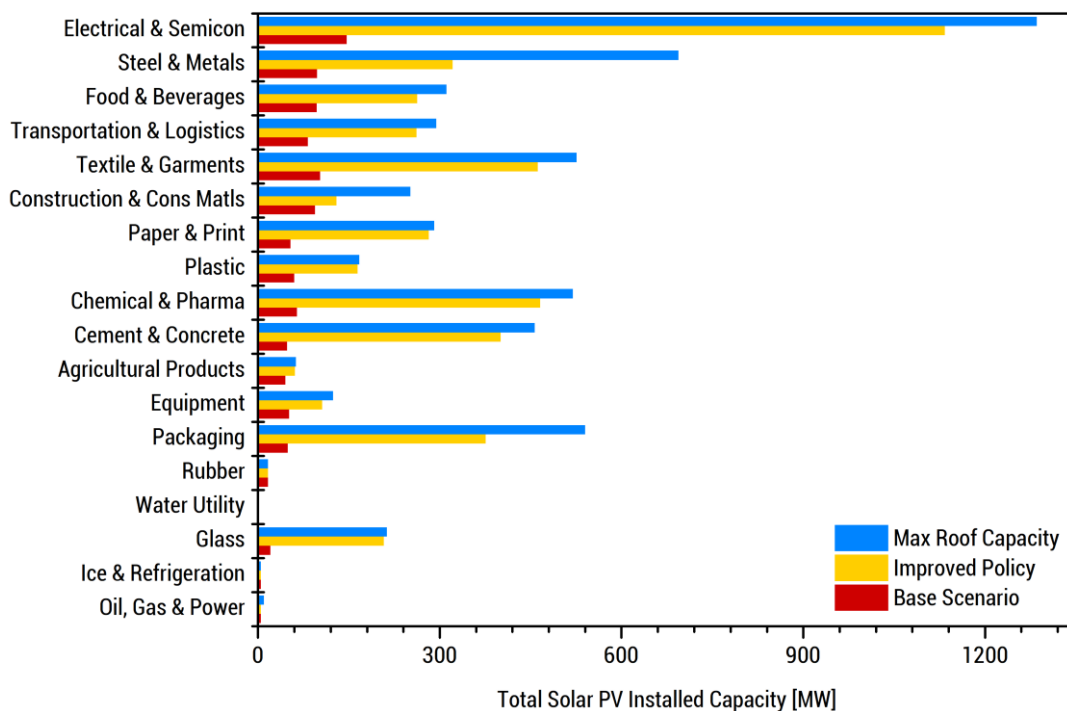


Figure 8. Total rooftop solar PV potential of the sampled industrial plants under different scenarios.

3.3.2. Economic Potential

Figures 9–11 show the LCOE, NPV, and CO₂ emission reduction, respectively, of each sub-industry under the different grid-tied scenarios.

Most of the sub-industries have an optimized LCOE of around USD 0.17/kWh to USD 0.186/kWh, while only the Oil and Gas sub-industry has exceeded the average electricity retail price of ~USD 0.19/kWh. Sub-industries with low energy intensities (Construction and Construction Materials, Transportation and Logistics, and Food and Beverages) generally exhibited a lower optimized LCOE.

Meanwhile, energy intensive sub-industries (Electrical and Semiconductors, Cement and Concrete, Steel and Metal, and Textile and Garments) accounted for higher NPV and lower CO₂ emissions as these parameters are directly influenced by electricity demand and, hence, the larger effect of rooftop solar PV installation. This demonstrates the effect of a facility’s energy consumption on the LCOE, NPV, and CO₂ reduction upon the integration of rooftop solar PV.

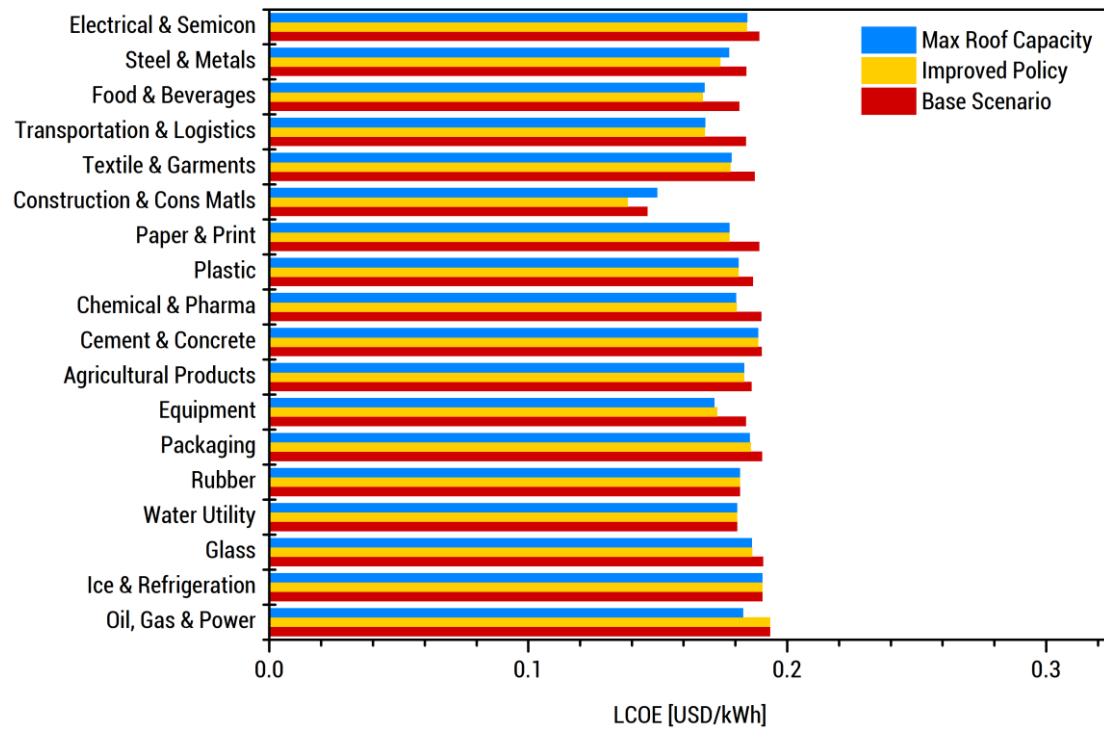


Figure 9. Levelized cost of electricity (LCOE) of the sampled industrial plants under different scenarios.

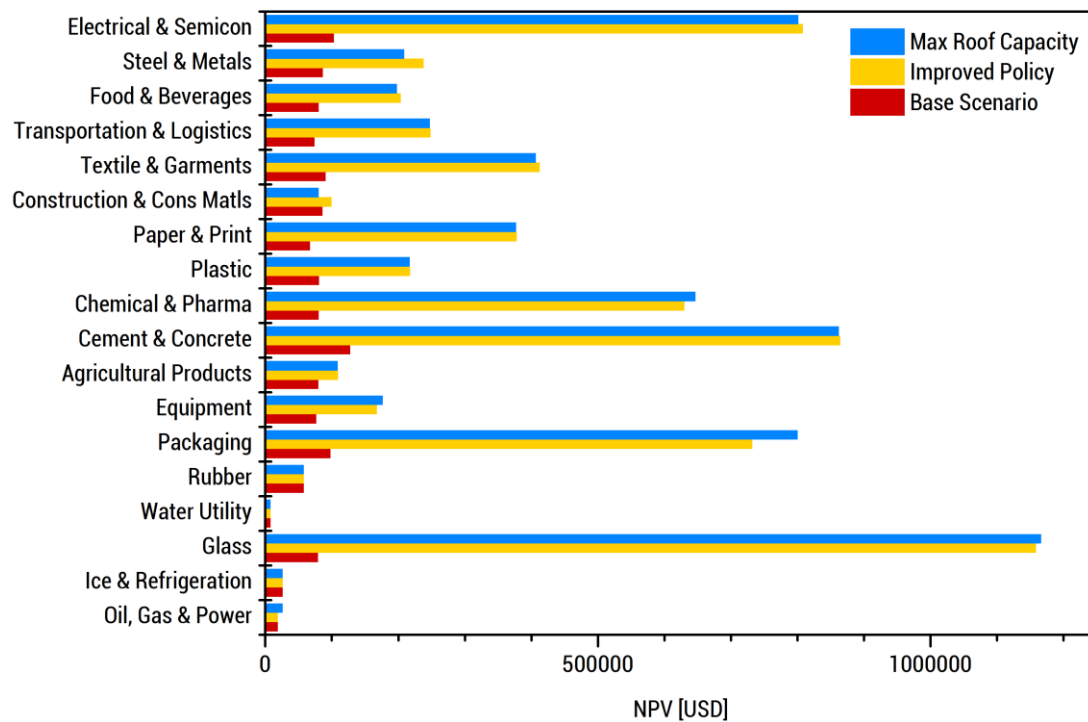


Figure 10. NPV of the sampled industrial plants under different scenarios.

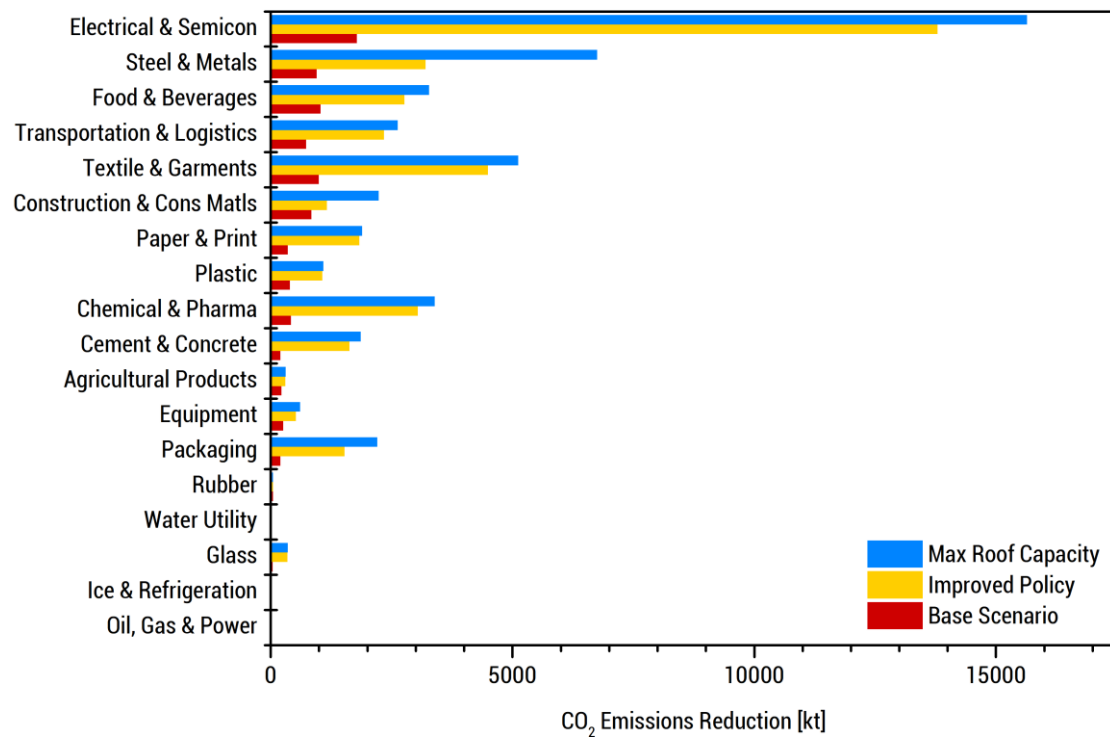


Figure 11. CO₂ emission reduction of the sampled industrial plants under different scenarios.

3.3.3. Investment Potential

Figures 12 and 13 show the IRR and PBP, respectively, of each sub-industry under the different grid-tied scenarios.

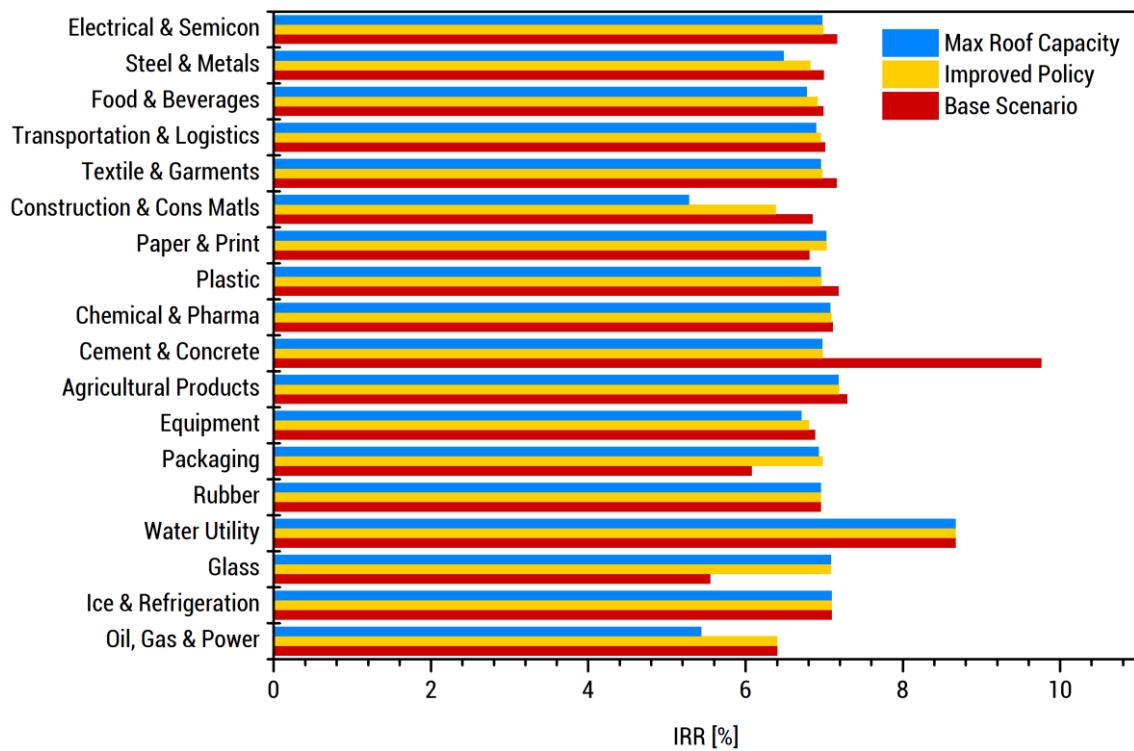


Figure 12. IRR of the sampled industrial plants under different scenarios.

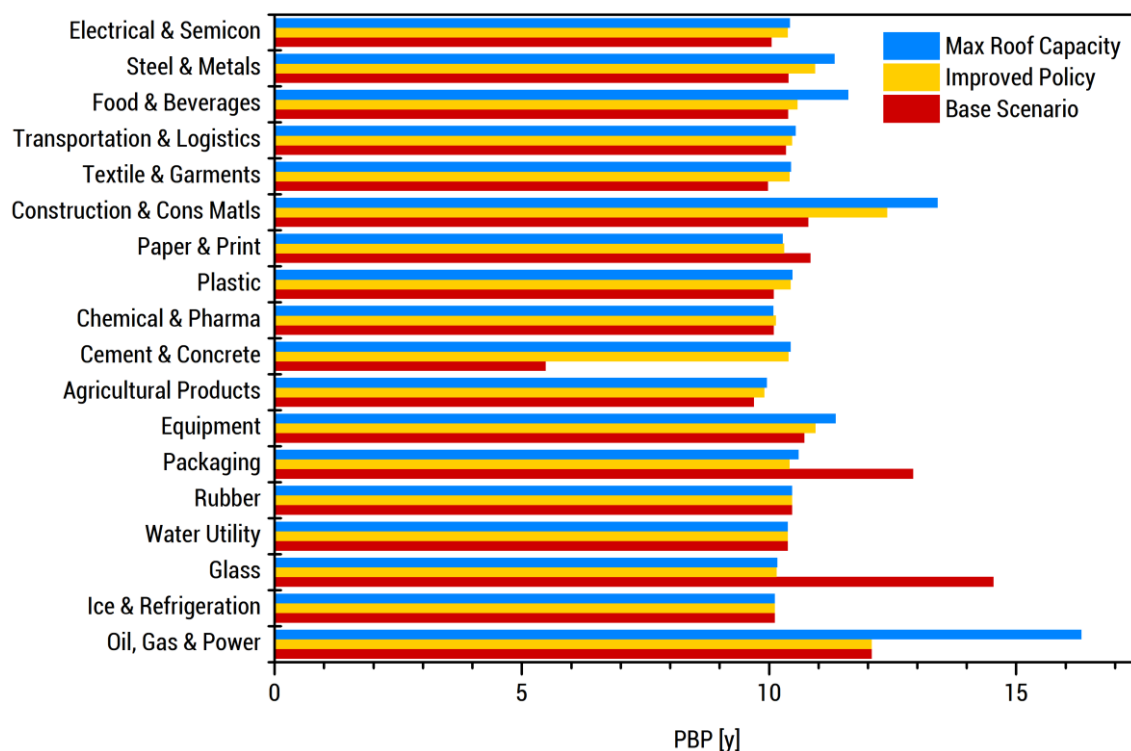


Figure 13. PBP of the sampled industrial plants under different scenarios.

The IRR values of the additional sub-industries considered in this work averaged 6%–7%, which is slightly lower than the IRR of those considered in our previous work. Nonetheless, this is still higher than the 4% interest rate in 2019 [28], indicating minimal investment risk upon the deployment of rooftop solar PV. This is particularly true for energy intensive sub-industries, which are characterized by high IRR and low PBP values. In contrast, sub-industries with a low energy consumption had a higher PBP and an IRR near the 4% interest rate.

3.3.4. Overall Potential

From the results presented above, it is evident that rooftop solar PV is a more favorable investment particularly for energy intensive sub-industries. This is primarily because low energy intensity sub-industries have solar PV potentials higher than the demand of the plant. Excess solar energy generated by the system will then be sold to the grid. It is more economical, however, to utilize all the generated solar energy because electricity is sold at a rate of USD 0.076 kWh only as opposed to the retail electricity rate of ~USD 0.19/kWh. This explanation is validated by the findings from the Max Roof Capacity scenario wherein the investment efficiency decreases due to the increase in solar PV potential against the demand. This was also observed in our previous study [15] wherein the savings incurred from rooftop solar PV does not always compensate for the high capital costs.

3.4. Off-Grid Scenario Results

Table 7 shows the results describing the application of the Off-Grid scenario.

Of the 139 industrial facilities surveyed in this work, 14 of these (~10%) were viable for off-grid electrification. This consists of the seven viable facilities from our previous work and seven more facilities included in this study. Six of these facilities may use either lithium-ion or lead–acid batteries as energy storage. Four other industries can deploy only the lithium-ion battery, while the remaining four can utilize only the lead–acid battery. Off-grid solar PV systems employing the lead–acid battery have higher investment efficiencies based on the IRR and PBP. On the other hand, systems that have lithium-ion as energy storage benefit from higher energy storage capacities, NPV, and reduction in CO₂

emissions. The viability of the Off-Grid scenario depends largely on the behavior of their load profile and the rooftop area. The industrial plants' profile must have high energy usage during night-time and low energy usage during daytime to make it viable for off-grid application. It must also have a large rooftop area to obtain a solar PV potential that can supply both the batteries and the facility's energy demand.

Table 7. Summary of results on the Off-Grid scenario.

Metrics	Solar PV + Diesel + Lead–Acid Battery	Solar PV + Diesel + Lithium-Ion Battery
Average solar PV installed capacity (kW _p)	158.6	158.6
Total solar PV installed capacity (MW _p)	283.8	283.8
Average energy storage capacity (kWh)	12.7	69.7
Total energy storage capacity (MWh)	16.2	89
LCOE (USD/kWh)	0.4	0.43
NPV (USD)	237,405	316,221
IRR (%)	5.35	4.4
PBP (y)	15.6	19.6
Average reduced CO ₂ emissions (tons of CO ₂)	138.26	192.41

3.5. Sensitivity and Grid Defection Analysis

A sensitivity analysis was performed to illustrate the effect of the decreasing prices of solar PV and lithium-ion batteries over time on the optimum system configuration. The cost of solar PV and energy storage are projected to decrease as materials and manufacturing processes are always being improved. The increased production of these technologies also leads to economies of scale. In particular, the New Energy Outlook of the Bloomberg New Energy Finance predicts a 71% drop in solar PV costs by 2050 [29]. Meanwhile, lithium-ion battery prices will experience a 33% decrease by 2030 and a 50% decrease by 2050 [30]. This case study is based on a sample packaging plant with a rooftop area of 12,445 m² and a maximum solar rooftop capacity of 1938.6 kW_p. This plant has an optimized solar PV and lithium-ion storage potential of 743.2 kW_p and 1.5 kWh in 2019, respectively, with a corresponding LCOE of USD 0.42/kWh.

Figure 14 demonstrates the increasing optimum potential of solar PV and lithium-ion battery installations as their cost decreases through the years. The potential of solar PV exhibited a consistent increase, while that of lithium-ion rose sharply by 50% at around 2040. The increasing renewable energy potentials also results in a reduction of CO₂ emissions.

A grid defection study shown in Figure 15 was also performed to identify the point when the off-grid generation costs (LCOE) will be comparable to the retail electricity price. The optimum LCOE of the off-grid configuration experiences a slow decline from USD 0.42/kWh from 2019 to USD 0.38/kWh in 2050. The LCOE of the off-grid system and the electricity rate from the grid [31] are predicted to intersect around the year 2040 with a generation cost of ~USD 0.397/kWh. Therefore, industrial consumers may consider defecting from the grid around 2041. The reduced electricity costs will consequently improve the investment quality of rooftop solar PV installation.

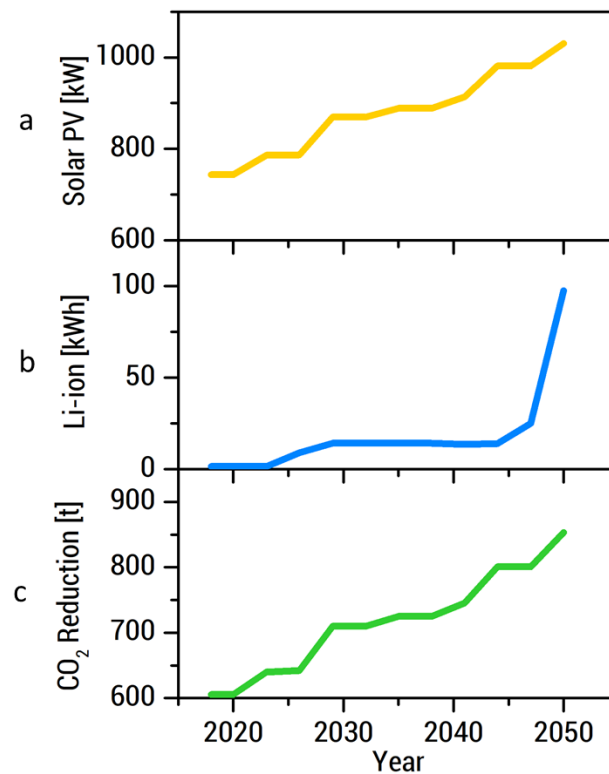


Figure 14. Sensitivity analysis results showing the (a) solar PV potential, (b) lithium-ion storage potential, and (c) CO₂ emission reduction over time for a sample industrial facility.

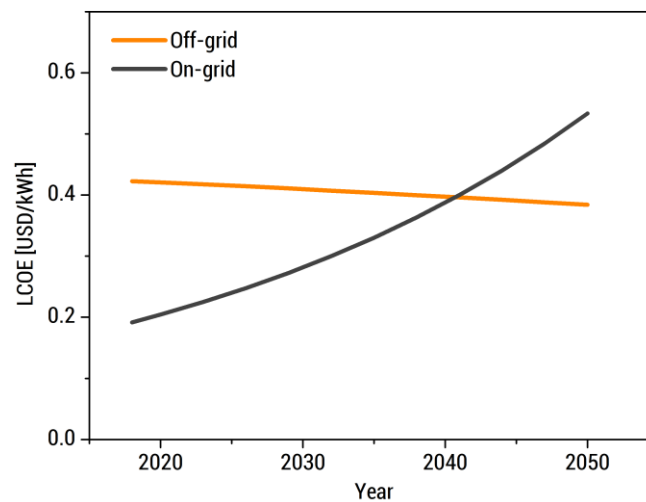


Figure 15. Grid defection analysis results showing off-grid system LCOE and the projected retail electricity price in the MERALCO franchise area in the Philippines.

4. Conclusions

In this work, we demonstrated a techno-economic assessment framework that can be utilized by policymakers to evaluate the effect of changing policies to encourage more investments from the private sector and by industrial facilities in the Philippines to determine the viability of implementing rooftop solar PV. Additional conclusions from this study are outlined below.

- The untapped rooftop solar PV potential of the sampled industrial establishments is about 1035 MW_p under the current net metering policy of the Philippines. This installed capacity

is comparable to a large-scale coal power plant in the Philippines, which ranges from 500 to 1200 MW.

- Relaxing the 100 kW_p net metering restriction will increase the total rooftop solar PV potential to 4654 MW_p, concurring our initial results on the impact of net metering policies on the deployment of solar PV-based energy systems.
- A decline in the performance of economic indicators such as IRR and PBP was observed under the Max Roof Capacity scenario for several sub-industries due to the increase in capital investment requirements.
- Energy intensive industries such as Electrical and Semiconductors, Cement and Concrete, Steel and Metals, and Textile and Garments will greatly benefit from the integration of rooftop solar PV due to increased savings, higher investment quality, and reduced CO₂ emissions.
- Some industrial plants can be powered by off-grid hybrid systems. The viability of this configuration depends on the load profile and rooftop solar PV potential.
- The optimum installed capacities, economic parameters, and investment efficiencies are highly dependent on solar PV and lithium-ion battery prices.
- Grid defection for some industrial establishments within the MERALCO franchise may occur as solar PV and lithium-ion batteries prices are declining continuously.

This framework can be applied to other electricity consumers, such as commercial and government establishments. The study can also be extended to other distribution utilities in the Philippines to create a nationwide rooftop solar PV resource assessment. Such a study may reduce land allocation for ground-mounted solar PV installations. Different compensation schemes for prosumers can also be investigated as this will affect the viability of rooftop solar PV systems, which could be patterned after net metering policies in other countries. Lastly, technical considerations, such as solar tracking, can be incorporated in future work.

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Nomenclature

Abbreviation	Meaning
ILP	Interruptible Load Program
IRR	internal rate of return
ISLA	Island System LCOE _{min} Algorithm
LCOE	levelized cost of electricity
MERALCO	Manila Electric Railroad and Light Company
NGEF	national grid emission factor
NPV	net present value
PBP	payback period
PV	photovoltaic

Appendix A

The economic values used in this work are presented in Table A1. Most of these are based on 1st Quarter 2019 Philippine market prices. The operating cost, project duration, and asset life are based on an existing study.

Table A1. Economic values and assumptions used in this work.

Economic Data	Value	Reference
Discount rate	4%	1Q Forecast for 2019 [28]
Inflation rate	2.08%	1Q Forecast for 2019 [32]
Grid price	0.19 USD/kWh	1Q 2019 Average Local DU ¹ Rate [33]
Net metering rate	0.076 USD/kWh	1Q 2019 Average Local DU ¹ Rate [33]
Project duration	25 years	
Solar PV capital cost	1133.5 USD/kW	Based on 1Q 2019 market price of surveyed solar PV panels. Includes cost of polycrystalline solar PV panels, inverter, and frames
Solar PV annual operational costs	23.85 USD/kW	Based on previous study [3]
Solar PV material life	25 years	Based on previous study [3]
Diesel fuel price	0.59 USD/L	Department of Energy [34]
Fuel inflation rate	4.08%	From EIA ² forecast up to 2050 [35]
Diesel generator capital cost	534.48 USD/kW	Based on 1Q 2019 market price of surveyed diesel generators
Diesel generator operating cost	0.05 USD/kW/year	Based on previous study [3]
Diesel generator equipment life	10 years	Based on previous study [3]
Lead–acid battery capital cost	157.06 USD/kWh	Based on 1Q 2019 market price of surveyed deep cycle lead–acid batteries
Lithium-ion battery capital cost	922.9 USD/kWh	Based on 1Q 2019 market price of surveyed lithium-ion Batteries
Charge controller capital cost	385.3 USD/kWh	Based on 1Q 2019 market price of surveyed battery charge controllers

¹ DU—distribution utility, ² EIA—Energy Information Administration.

Appendix B

The technical values used in this work are presented in Table A2. These are the specifications of equipment often used by customers of the local distribution utility (MERALCO), except for several battery parameters which were based on an existing study.

Table A2. Technical values and assumptions used in this work.

Technical Data	Value
Polycrystalline solar PV panel area	6.42 m ² per 255 W module
Polycrystalline solar PV derating factor	0.77
Polycrystalline solar PV temperature coefficient	0.004167 °C ⁻¹
Diesel generator spinning reserve [36]	15%
Maximum depth of discharge of battery [37]	0.8
Charging efficiency of battery [37]	0.895
Discharging efficiency of battery [37]	0.895
Maximum number of cycles for lead–acid battery	1500
Maximum number of cycles for lithium-ion battery	5000

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