Energetic and Economic Viability of off-grid PV-BESS for Charging Electric Vehicles: Case Study of Yogyakarta

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Abstract. Photovoltaic and Battery Energy Storage System (PV-BESS) is a system for utilizing solar energy. The off-grid PV-BEES design is used for vehicle electric charging stations to ensure the security of the electricity supply and is economically feasible. The HOMER application is used in this study to simulate energetic and economic feasibility. As a result, the offgrid system produces energy of 474,027 kWh/year, consumes energy of 1,957 kWh/year, the excess energy of 471,968 kWh/year, and the value of NPC, COE, ROI is Rp.733,403,300.00, Rp.17,783.04 and -7% respectively. At the same time, the improvised system, by turning it into an on-grid, produces energy, consumed energy, and excess energy of 553,985 kWh/year, 517,790 kWh/year, and 14,410 kWh/year, respectively. For the value of NPC, COE, and ROI, respectively, Rp.934,259,900, Rp.85.63, 46.6%. Finally, it can be said that offgrid PV-BESS is a practical choice for doing more than only lowering emissions by utilizing solar energy. Off-grid PV-BEES has a tremendous excess energy of 471,968 kWh annually. According to energy analysis, it has a high COE value. Propose to Improve an on-grid system. Improvements were made that allow excess energy to be shared with other customers. According to economic analysis, this makes the system more cost-effective, with a potential payback in the second year.

1 Introduction

The Indonesian energy model exhibits warning indications of unreliability, an uncontrollable increase in demand and CO_2 emissions, and a heavy reliance on coal, oil, and natural gas (Figure 1). The electricity generation industry will contribute the most to overall emissions in 2021, at about 49.8%, followed by the transportation and industrial sectors, at 23.7% and 16.1%, respectively, be emissions reaching 607 million tons of CO2 in 2021. (Figure 2) depicts the growth of CO2 emissions from 2012 to 2021 [1]. The similarities between the current energy and the oil price shock of the 1970s include slowes growth, rising inflation, high commodity costs, and tigh labor markets [2].

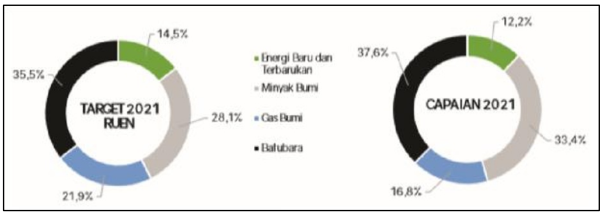

Fig. 1. Final energy consumption in Indonesia 2015-2021.[3].

The transportation sector accounted for 40% of the total final energy consumption (excluding traditional biomass) in 2018, followed by industry (36%), households (16%), businesses (16%), and other sectors (6% and 2%), in that order. The figure for CO2 emission from fuel consumption is shown in Figure 2 [4].

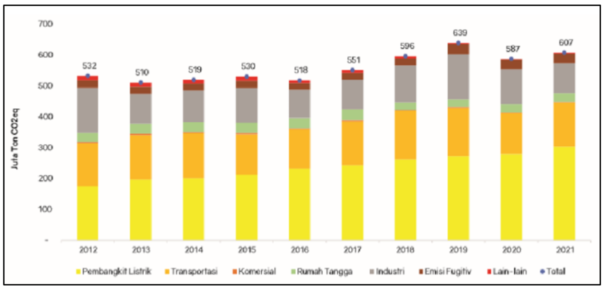

Fig. 2. CO_2 Emissions from Fuel Combustion 2021 [3].

Electric vehicles (EVs) provide numerous significant environmental advantages. For instance, the effect of transportation on air pollution is significant in metropolitan regions, where the majority of transportation operations occur [5]. The generation of traditional electricity, which is still necessary for charging electric vehicles, results in a concentrated accumulation of carbon dioxide at power plants.

Indonesia has enormous solar energy potential. Spain's horizontal surface receives an annual average of

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1640 kWh/m2 of global irradiation. The potential solar energy in Indonesia is shown in Figure 3. The potential for solar energy in Indonesia is enormous, with a 3294.4 GW energy potential and an average yearly worldwide irradiation of 4.66 kWh/m2 [3], [6]. In 2021, solar PV generation surpassed 1 000 TWh and rose by a record 179 TWh, and 22% increase from 2020. 3.6% of the world's electricity is produced with solar photovoltaics. Of all renewable technologies, it showed the second-largest absolute generation growth in 2021, right behind wind. However, to adhere to the Net Zero Emissions by 2050 Scenario, the yearly generation increase must average 25% from 2022 to 2030. This results in an increase in yearly capacity deployment of more than three times until 2030, creating policy, legislation, and funding issues. (International Renewable Energy Agency (IRENA), 2022) [7], [8].

Several pieces of literature, like [9], study the energy EVs need to charge on the grid and examine current implementations of EV charging controls and optimization techniques for energy management. [10] propose a coordinated control system for photovoltaic (PV)-based EV charging stations based on the intelligent energy management scheme (IEMS). The IEMS analyzes current meteorological and load demand data to maximize PV generation and grid power use for EV charging stations (EVCS). Moreover, [11] explored a network application for electric vehicle (EV) charging and local consumption of distributed solar electricity.

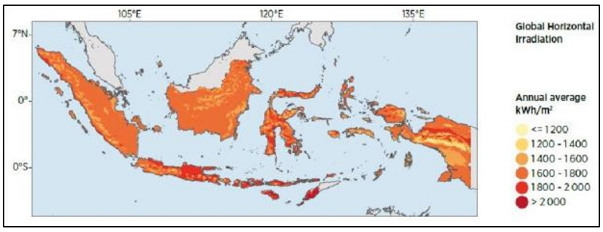

Fig. 3. CO_2 Emissions from Fuel Combustion 2021 [3].

Adopting meteorological data from the Indonesian city of Yogyakarta, the suggested work in this research focuses on the technical, financial, and environmental advantages of adopting off-grid PV-BESS for charging EVs. To reduce emissions and provide a highly effective off-grid PV-BESS system, this research article intends to create a system that has the lowest investment need among the choices. After that, the profitability and dependability of each solution are assessed by contrasting the off-grid PV-BESS with a grid-connected system. Consequently, a typical off-grid PV-BESS is one that consists of a PV plant, a BESS, and an EV charger. By storing electricity that cannot be utilized immediately and using it when the demand for PV power cannot be met, the BESS helps assure the supply's security. At each sample time, the battery inverter controls the delivery and storage of the available energy. The off-grid PV-BEES is shown in Figure 4.

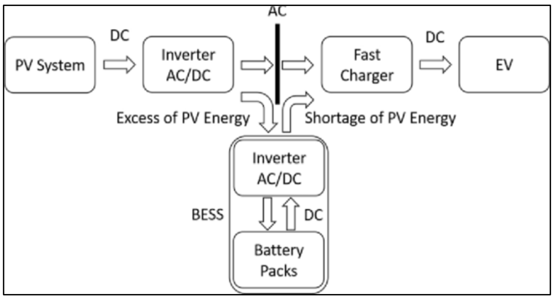

Fig. 4. The off-grid PV-BEES System.[12]

The study is performed using HOMER software since it is distinguished by a strong performance in assessing the energetic, financial, and environmental aspects of projects based on sources of renewable energy (Homer Pro) [13]. The most significant contribution to this study is estimating the ideal off-grid PV-BESS size for EV charging, followed by improving the outcomes utilizing the loads' shifting technique.

2 Experimental Methods

2.1 HOMER software for sizing Materials

In the literature, several software tools, including PVsyst and HOMER, are used to assess the ideal design of PV installations. PVsyst is a piece of software for analyzing, simulating, and investigating entire PV systems. HOMER is a software application used to create hybrid microgrids that are optimized. Homer can compare multiple configurations in a single experiment and shows the effects of uncontrollable factors like wind speed, fuel cost, inflation rate, etc. The system's viability and profitability for installation are determined by the simulation findings. As a result, different system configurations can be compared. As a result, it is possible to see how the variables are affected. The off-grid PV-BESS in this study was designed by HOMER.

2.2 Modeling

2.2.1 PV module

To calculate the power generation is formulated by

$$PP_{PV}=Y_{PV}f_{PV}\left(\frac{\overline{G_T}}{\overline{G_{T,SCT}}}\right)\left[1+\alpha_P\left(T_C-T_{C,STC}\right)\right] \quad (1)$$

Where: Y_{PV}: is the rated capacity of the PV array, meaning its power output under standard conditions (kW), f_{PV}: is the PV derating factor (%), $\overline{G_T}$ is the solar radiation incident on the PV array in the current time step (kW/m2), $\overline{G_{T,SCT}}$: the incident radiation at standard conditions (1 kW/ m2), αp: the temperature coefficient of power (%/°C), Tc : the PV cell temperature in the current time step (°C), Tc,STC: the PV cell temperature under standard conditions (25 °C).

2.2.2 Solar source

Homer calculates the global radiation on the tilted PV array using the equation:

$$\overline{G_T} = (\overline{G_b} + \overline{G_d}A_i)R_b + \overline{G_d}(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + \overline{G_{\rho_g}}\left(\frac{1-\cos\beta}{2}\right) \quad (2)$$

Where: G: the global horizontal radiation on the earths surface averaged the time step (kW/m2), $\bar{G} = G_b + G_d\left\{\frac{\overline{G_b}}{\overline{G_d}}\right\}$, $\overline{G_b}$:The bream radiation kW/m2, $\overline{G_d}$: The diffuse radiation kW/m2, $\overline{G_o}$: the extra-terrestrial horizontal radiation averaged over the time step (kW/m2), A_i = the anisotropy index → $A_i = \frac{\overline{G_b}}{\overline{G_o}}$, R_b : the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface, $R_b : \frac{\cos\theta}{\cos\theta_z}$, θ: Angel of the incident, θ_z: zenith angel β : the slope of the surface (°), f: the cloudiness, ρ_g: the ground reflectance, which is also called the albedo (%).

2.2.3 Batteries

The number of batteries in BEES is calculated by

$$N_{batt} = \frac{A_{batt}L_{prim.ave}(\frac{1000Wh}{kwh})}{V_{nom}Q_{nom}(1 - q_{im}/100)\,(24h/d)} \quad (3)$$

Where: A_{batt}: BESS autonomy (h), V_{nom}: nominal voltage of a single battery (V), Q_{nom}: nominal capacity of a single battery (Ah), q_{min}: minimum state of charge of the battery (%), $L_{prim,ave}$: average primary load (kWh/d).

2.2.4 Economic analysis

This section details an economic study of the considered off-grid PVBESS. The following indicators are used to evaluate the stability of the studied system. A project's net present value (NPV) is the difference between the value being recovered and the project cost[14].

$$NPV = \sum_t^T \frac{E}{(1+r)^t} - \cos t \quad (4)$$

Where E is annual returns in terms of wages, r is the discount rate, t is the number of working years, and the cost is the initial investment. The NPC lists the installation and operating costs over the system's lifetime, considering all components but subtracting salvage.

$$NPC = CC + RC + O\&M + FC - S \quad (5)$$

Where NPC is Net Present Cost, CC is Capital Cost, RC = Replacement Cost, $O\&M$ = Operational & Maintenance Cost. The system's average cost per kWh of electrical energy produced is COE. In general, COE is calculated using the following equation:

$$COE = \frac{TAC}{L_{prim.ac}L_{prima.dc}} \quad (6)$$

Where COE is the energy cost, TAC is the total annualized cost, $Lprim$, c is the primary load ACand $Lprim,c$ is primary load DC. IRR represents the discount rate for which the NPV of the project equals zero [14]. It is given by the equation:

$$\sum_t^n = 0\frac{NT_t}{(1+IRR)} - I_o = 0 \quad (7)$$

Where n is the period for which the analysis is conducted, I0 is the initial investment made in the project, and NTt is the asset flow at the period t's end. ROI is a typical performance metric used to assess an investment's effectiveness or to compare the effectiveness of several distinct investments [15], and it is given by equation

$$ROI = return - invesment. \quad (8)$$

2.3 Application to study case

2.3.1 Location of the off-grid PV-BEES

The location of the present project is the city of Yogyakarta, Indonesia (latitude= 7°.50 and longitude 110°.22). The time it takes to fill the tanks of internal combustion engine (ICE) vehicles with gas is shorter than the time it takes to charge an electric vehicle (EV). In contrast to ICE vehicle drivers, EV customers are more likely to use the extra time to do other things while charging[16]. So the location of the charging station is advisable to be close to recreation areas.

With an average annual solar irradiance of 4.8 KWh/m2/day and a high clarity index (0.4; 0.6), Yogyakarta has a high solar irradiance level, resulting in minimal cloud cover and high solar radiation reaching the PV array. The maximum solar radiation is 5.5 KWh/m2/day in September, and the lowest is 4.2 KWh/m2/day in January. Yogyakarta has ample solar energy resources. Thus it is essential to consider the viability and benefits of off-grid PV-BESS for charging EVs in this city to lower the amount of air pollution. The solar index and clearness index in Yogyakarta is shown in Figure 5. 2. Load profile of the off-grid PV-BESS

2.3.2 Load profile of the off-grid PV-BESS

The charge acceptance rate of the vehicle battery, which is controlled by the battery's energy management system, can vary between different EV models and depends on the rate of charge [17]. Fast charging is only possible up to 80% of the way because of hysteresis effects when the battery is almost fully charged.[16]. Various variations in the capacity of EV batteries have been scattered. The capacities of various types of EV batteries can be seen in Table 1 [9]. The fast charging units deliver the charge through direct current (DC) from a three-phase electrical grid and have a nominal output power of 50 kW. The EV battery size employed in this study is 60 kWh, and the fast charging procedure would take one hour to complete. As a result, the fast charger is operational at a load of 52,8 kW for one hour, as specified in the equation.[18]. The load profile scheme is shown in Figure 6.

$$Pf = 0.96$$

$$S = 55\ KVA$$

$$P = S.Pf = 55\ .\ 0{,}95 = 52{,}8\ kW$$

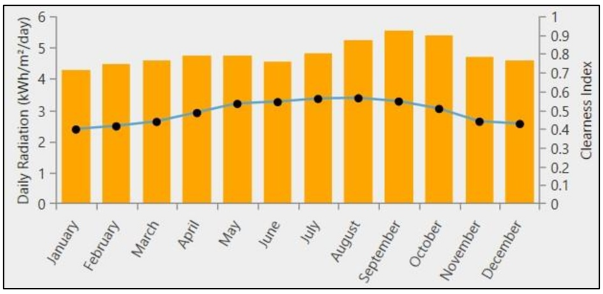

Fig. 5. The solar index and clearness index in Yogyakarta

Table 1. This is the table of various variations in the capacity of EV batteries

EV Brand	Battery Capacity
Tesla Model 3	60 kWh
Hyundai IONIQ6	58 kWh
Renault Megane E-Tech	60 kWh
Peugeot-e-308 SW	54 kWh
Fiat 500 e Hatchback	24 kWh
Mini Cooper SE	32.6 kWh

2.4 Description of the installation components

2.4.1 Components of the off-grid PV-BESS

As shown in Table 2, the following elements were selected for the installation's design. All parts (solar inverter, battery inverter, and charger) are coupled to a conventional 400 V AC bus. Table 2 lists the technical specifications of these components [19][20][18].

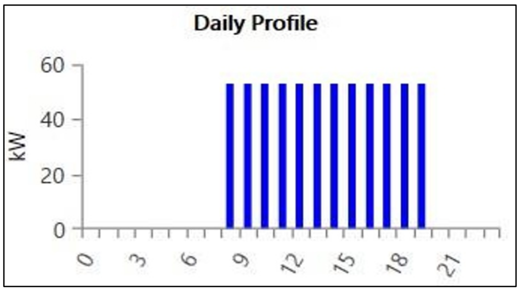

Fig. 6. The load profile scheme

Table 2. This is the table of technical spesifications of components

PV Module	Standard Conditions	PV Inverter	Data	BESS	Data	Fast Charger	Data
Pmax	340 W	Vol range	585 to 820 V	Type	Lithium Iron Phosphate	Charging standard	CCS and CHAdeMO
Vmp	38,3 V	I max (DC)	750 A	Capacity	100 kWh	Maximum output power	50 kW
Imp	8,88 A	Pmax (AC)	450 kW	Voltage	600 V	Output voltage range	50 – 500 VDC
Voc	46,73 V	Imax (AC)	666 A			Maximum output current	125 ADC
Isc	9,51 A	Vmax (AC)	390 V			Input voltage range	400 VAC
Surface	1,941 m2	Efficiency	96,10%			Max. Rated input current	80 A
Efficiency	17,49 %					Max. Rated input power	55 kVA
						Power factor	0,96

3 Result and discussion

3.1.1 Analysis of energetic criteria

According to a simulation performed using HOMER, a solar panel's maximum output is 314 kW, producing 474,027 kWh of energy per year while using 1,957 kWh of energy annually. A very high energy generation level results in excess energy production of 471,968 kWh per year with a 99.6% efficiency and an annual unmet load value of 229,307 kWh. Technical and energetic results are shown in Table 3.

Table 3. This is the table of technical and energetic results

Generated energy (kWh/year)	Consumed Energy (kWh/year)	Excess energy (kWh/year)	Excess energy (%)	Unmet load (kWh/year)
474,027	1,957	471,968	99,6	229,307

3.1.2 Analysis of economic criteria

The examination of NPC (5), COE (6), and ROI (7) indicators are used to carry out the investment analysis. The results are displayed in Table 4. The fundamental case study considers Battery and inverter life for fifteen years. As a result, they need to be replaced in the middle of the project. The 30year useful life of PV module inverters is the time frame to evaluate all investments. The NPC value is Rp. 733,403,300, and the COE is quite expensive, Rp. 17,783.04, with a ROI value of minus 7%, according to the data shown in Table 4.

Table 4. This is the table of economic analysis results

Devices	Investment (Rp)	Discount Rate (%)	NPC (Rp)	COE (Rp)	ROI (%)
PV Modules	62,304,933.47				
Inverter	1,204,853.20				
BESS	150,081,000.00				
system					
	213,590,786.67				
Total	427,181,573.34	5,75	733,403,300	17,783.04	-7

3.1.3 Improvement study case

As shown in Table 3, solar panels produce significant excess energy. In addition, the cost of recharging may be less expensive than in the default scenario. In this instance, the enhancement entails designing the current system to be ongrid, which maximizes the sale of the extra electricity. This suggested change aims to accelerate cash flow and maximize solar resources.

- *Analysis of energetic criteria*

The outcomes match the energy requirements for the improvised case study shown in Table 5. As shown, the excess energy generated by PV reduced to 2.6%, indicating that the on-grid system channeled the excess energy out. With the improvisation schema, the annual energy production is 553,985 kWh, and the annual energy consumption is 517,790 kWh. The average electric production is shown in Figure 7.

Table 5. This is the table of technical and energetic results of the improved study case

Component	Generate energy (kWh/year)	Consumed Energy (kWh/year)	Excess energy (kWh/year)	Excess energy (%)	Unmet load (kWh/year)
PV	474,027	231,264	14,410	2.6	0
Grid	79,958	286,526			
Total	553,985	517,790			

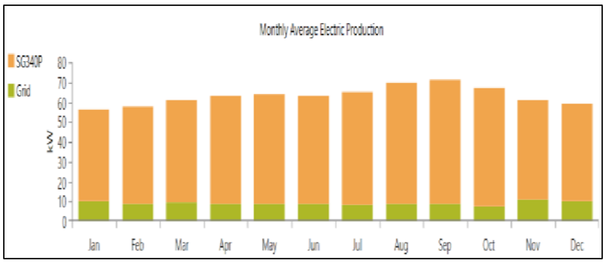

Fig. 7. Monthly average electric production

- *Analysis of economic criteria*

The economic analysis of the improved case study is shown in Table 7. According to the data, the investment decision would be advantageous, which shows that the NPV is Rp. 934 259 900, the COE small value is Rp 85.63, the ROI growth is now 46.6%, the IRR is relatively high at 54.5%, and the payback can be achieved in the second year. As a result, the economic and energetic analyses show that employing the modified case study will result in more favorable outcomes. The cash flow of the improved study case is shown in Figure 8. Figure 9 shows the differences between grid purchase and sale in the improved study case.

Table 6. This is the table of economic analysis of the improved study case

Devices	Investment (Rp)	Discount Rate (%)	NPC (Rp)	COE (Rp)	ROI (%)	IRR (%)	payback (year)
PV Modules	62,304,933.47						
Inverter	1,204,853.20						
BESS	150,081,000.00						
system	803,657,238.47						
Total	1,017,248,025.14	5,75	934,259,900	85.63	46.6	54.5	1.76

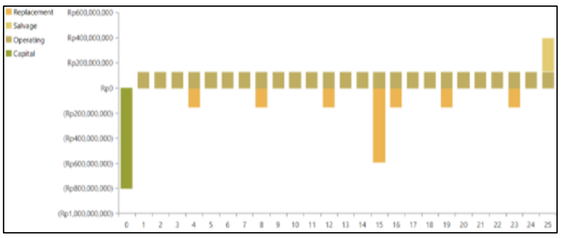

Fig. 8. The cash flow of improved study case

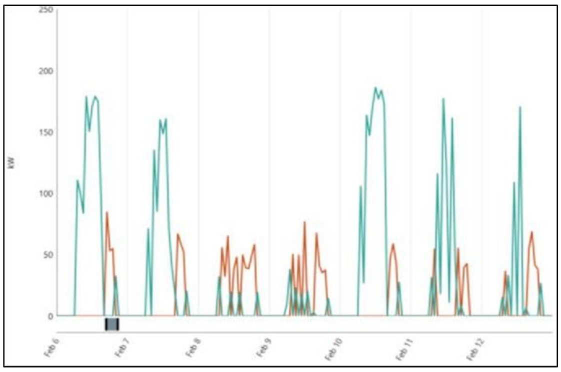

Fig. 9. The differences between grid purchase and grid sale in the improved study case

4 Conclusion

An energy and financial analysis of an off-grid PV-BESS has been carried out in this research. In order to ensure system efficiency and produce an affordable charging process for EVs, and be economically feasible. In conclusion, off-grid PV-BESS is a viable option for more than just reducing emissions through solar energy. According to energy analysis, PV-BEES off-grid has a significant energy surplus of 471.968 kWh annually and a high COE value, according to economic analysis. Improvement is made by switching to an on-grid system so that surplus energy may be shared with other customers, and, based on economic analysis, this makes the system more economical, with payback returns possible in the second year.

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References

1. IESR, “Indonesia Energy Transition Outlook 2021,” Iesr, pp. 1–93, (2021).
2. IEA, “World Energy Outlook,” (2022).
3. Tim Sekretaris Jenderal Dewan Energi Nasional, “2 0 2 2,” (2022).
4. Tim Sekretaris Jenderal Dewan Energi Nasional, “Indonesia Energy Out Look 2019,” (2019).
5. O. Heidrich, G. A. Hill, M. Neaimeh, Y. Huebner, P. T. Blythe, and R. J. Dawson, “How do cities support electric vehicles and what difference does it make?,” Technol. Forecast. Soc. Change, vol. **123**, no. November 2016, pp. 17–23, (2017), doi: 10.1016/j.techfore.2017.05.026.
6. S. D. Prasetyo, A. R. Prabowo, and Z. Arifin, “Investigation of Thermal Collector Nanofluids to Increase the Efficiency of Photovoltaic Solar Cells,” vol. **40**, no. 2, pp. 415–422, (2022).
7. Z. Arifin, S. D. Prasetyo, D. D. D. P. Tjahjana, R. A. Rachmanto, A. R. Prabowo, and N. F. Alfaiz, “The application of TiO2 nanofluids in photovoltaic thermal collector systems,” Energy Reports, vol. **8**, no. May, pp. 1371–1380, (2022), doi: 10.1016/j.egyr.2022.08.070.
8. S. D. Prasetyo, A. R. Prabowo, and Z. Arifin, “The use of a hybrid photovoltaic/thermal (PV/T) collector system as a sustainable energy-harvest instrument in urban technology,” Heliyon, vol. **9**, no. 2, p. e13390, Feb. (2023), doi: 10.1016/j.heliyon.2023.e13390.
9. R. O. Kene and T. O. Olwal, “Energy Management and Optimization of Large-Scale Electric Vehicle Charging on the Grid,” World Electr. Veh. J., vol. **14**, no. 4, (2023), doi: 10.3390/wevj14040095.
10. M. Amir, Zaheeruddin, A. Haque, F. I. Bakhsh, V. S. B. Kurukuru, and M. Sedighizadeh, “Intelligent energy management scheme-based coordinated control for reducing peak load in grid-connected photovoltaic-powered electric vehicle charging stations,” IET Gener. Transm. Distrib., no. January, pp. 1–18, (2023), doi: 10.1049/gtd2.12772.
11. Q. He et al., “Research on a Charging Mechanism of Electric Vehicles for Photovoltaic Nearby Consumption Strategy,” Electron., vol. **11**, no. 20, pp. 1–22, (2022), doi: 10.3390/electronics11203407.
12. L. S. A. Grande, I. Yahyaoui, and S. A. Gómez, “Energetic, economic and environmental viability of off-grid PV-BESS for charging electric vehicles: Case study of Spain,” Sustain. Cities Soc., vol. **37**, no. July 2017, pp. 519–529, (2018), doi: 10.1016/j.scs.2017.12.009.
13. Z. Arifin et al., “Grid-Connected Hybrid PV-Wind System Simulation in Urban Java,” J. Eur. des Syst. Autom., vol. **55**, no. 4, pp. 477–483, (2022), doi: 10.18280/jesa.550406.
14. M. Kovač, S. Tadić, M. Krstić, V. Elia, and F. De Leo, “Stochastic financial evaluation: The case of an intermodal terminal,” Sustain. Futur., vol. **5**, no. June 2022, (2023), doi:10.1016/j.sftr.2022.100104.
15. Sandborn, “Return on Investment (ROI),” Online Video Revolut., pp. 87–105, (2012), doi: 10.1007/9781-137-51124-9_6.
16. C. Madina, H. Barlag, G. Coppola, I. Gomez, R. Rodriguez, and E. Zabala, “Economic assessment of strategies to deploy publicly accessible charging infrastructure,” World Electr. Veh. J., vol. **7**, no. 4, pp. 659–669, (2015), doi: 10.3390/wevj7040659.
17. Y. Motoaki and M. G. Shirk, “Consumer behavioral adaption in EV fast charging through pricing,” Energy Policy, vol. **108**, no. May, pp. 178–183, (2017), doi: 10.1016/j.enpol.2017.05.051.
18. ABB Inc., “Electric Vehicle Charging Infrastructure Terra SC, single outlet DC fast charging station,” p. 2, (2013).
19. Peimar, “peimar data sheet,” https://energypal.com/best-solar-panels-forhomes/peimar/sg340p, (2023).

20. Sinexcel, "Operating Manual PWS1-50K to 250K Series Energy Storage PCS Sinexcel PWS1-50K to 250K Series Bi-directional Energy Storage PCS Operating Manual," https://www.sinexcel.us/storage-inverters , (2023).