



Techno-economic modeling and analysis of a PV EV charged with battery energy storage system (BESS) on Kalimantan Island [☆]

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Abstract

This research examines the optimal combination of solar panel and battery capacity in hybrid systems in 11 cities on the island of Borneo, utilizing the region's significant solar energy potential and high irradiation levels. This research analyses the optimal combination of solar panels and battery capacity in 11 cities in Kalimantan using particle swarm optimization (PSO) and grey wolf optimization (GWO) algorithms to maximize energy output, reduce levelised energy costs, and maximally reduce carbon emissions. Results show Tarakan as the most optimal location, generating 215,804.88 kWh for IDR 916.9/kWh and lowering emissions by 435,884.29 kgCO₂e, while Samarinda is the least optimal location. Economically, electricity tariffs of IDR 2,466.78/kWh and IDR 2,000/kWh generate a positive Net Present Value (NPV) with a payback period (PP) of 9–12 years, while a tariff of IDR 1,500/kWh is considered unfavorable. The findings demonstrate the effectiveness of PSO and GWO in optimizing the renewable energy system and confirm the project's financial viability, with a positive NPV and reasonable PP. Implementing renewable energy systems in Kalimantan Island can improve energy efficiency and significantly reduce carbon emissions, supporting environmental sustainability goals.

Keywords: Techno-economic analysis; Electric vehicle; Electric vehicle charger; PSO; GWO

0 Introduction

Electrical energy has become one of the primary human needs, with many activities requiring this energy. A press release from the Ministry of Energy and Mineral Resources, dated January 15, 2024, reported that Indonesia's average per capita electrical energy consumption has reached 1,285 kWh [1].

With the advancement of this technology, electric energy has also developed so that it has begun to penetrate the world of transportation, which is marked by the ram-

part sale and use of electric vehicles, both two-wheeled and four-wheeled vehicles. Citing data provided by Data-book, the sales volume of electric cars in Indonesia reached 17.06 thousand units by the end of 2023. This value has increased by 65.2 % compared to the end of 2022 [2]. Electric car sales are dominated by the Hyundai Ioniq 5 Signature Long Range, with sales of Six thousand three hundred thirty-four units, followed by Wuling Air EV Long Range with sales of 3,461 units [3]. The widespread use of Electric Vehicles (EVs) is considered capable of reducing carbon emissions and transportation costs while improving air quality in urban areas [4]. These eco-friendly vehicles offer potential long-term savings for consumers, making them an attractive option for budget-conscious individuals [5]. As cities increasingly promote electric transportation, the benefits of EVs, such as reduced noise pollution, are becoming more apparent to

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Nomenclature

Symbol	Description	Symbol	Description
A_{PV}	Solar panel surface area (m^2)	N	Period of use of the project
AC	Alternating current	N_{batt}	Total battery requirement
BESS	Battery energy storage system	OD	Number of Days of Battery Autonomy
CAPEX	Capital cost	OPEX	Maintenance cost
C_t	Total outgoing costs in year t (Rp)	P_{PLTS}	Solar panel capacity (kWp)
CPSO	Constrained Particle Swarm Optimization	P_d	Load Power Used (kW)
C_{Tbatt}	Total battery capacity (kWh)	P_{inv}	Inverter capacity (kW)
C_{APEX}	Cost of initial capital employed	P_p	Payback period
$C_{F,N}$	Cash flow in period N	PV	Photovoltaics
DoD	Depth of Discharge	PSO	Particle Swarm Optimization
DC	Direct Current	r	Discount ratio
E_{out}	System output energy (kWh)	R	Revenue or revenue (Rp)
EV	Electric Vehicle	RE	Renewable Energy
EVCS	Electric Vehicle Charging Station	SF	Safety Factor (%)
EOM	Output Energy Maximization	SAM	System Advisor Model
eCO_2	Carbon emissions ($kgCO_2e$)	SPKLU	Public Electric Vehicle Charging Stations
E_f	Carbon emission factor ($0,757 kgCO_2/kWh$)	SGTCS	Solar-based grid-tied charging station
E_t	Energy generated at time t (kWh)	SoC	State of Charge
E_p	Energy generated (kWh)	TOE	Ton of Oil Equivalent
G	Solar Irradiation (kWh/m^2)	V_{batt}	Battery module voltage (V)
GCPV	Grid-Connected Photovoltaic	W_d	Daily electrical energy required (Wh)
GWO	Grey Wolf Optimization	W_s	Planned Electricity Demand (Wh)
I_{Cbatt}	Total Current of Battery Requirement (Ah)	WT	Electric Vehicle Charging Station
LCOE	Levelized Cost of Energi (Rp/kWh)	η_{inv}	Inverter efficiency (%)
N_{PV}	Number of Solar Panels	$\eta_{baterai}$	Battery efficiency (%)
N_{PV}	Net Present value	η_{PV}	Solar Panel Efficiency

both residents and policymakers [6]. This shift towards electrification in the transportation sector is not only addressing environmental concerns but also providing economic advantages and enhancing the overall quality of life in urban settings [7]. However, many countries, including Indonesia, still use coal-fired power generation systems [8], so the shift to EVs could be more helpful for energy conservation and emissions reduction. Furthermore, if there are many EVs on the road, charging them themselves will strain the electricity grid performance [9].

Quoted from the data contained in the Indonesian Energy Outlook 2023, the use of primary energy in Indonesia reached 246 million TOE, dominated by coal at 42 %, followed by oil at 31 %, and gas at 14 % [10]. RE use in this primary energy supply is only at 30 million TOE or only 12.3 % of the total primary energy supply [11]. The total utilization of EBT is only 12.6 GW, which is only about 0.30 % of the total RE potential in Indonesia. It has a value of 3,687 GW and a solar energy potential of 3,294 GW. The intensity of sunlight radiation in Indonesia can reach up to $4.8 kWh/m^2$ [12]. This level of solar irradiance is observed throughout the year [13]. Solar energy is the most widely available energy. With the abundance of solar energy potential, it can be utilized as an option in

energy generation to supply EV charging stations that are more environmentally friendly [14].

This research supported the Indonesian government's initiative to increase the renewable energy mix to 31 % by 2030 [15]. This study involved technical modeling and economic assessment of a solar power plant system serving as a power source for an electric vehicle charging station. The objective was to optimize the utilization of PV, batteries, and the electrical grid, considering criteria such as maximum E_{out} , minimum energy cost (Levelized Cost of Energy or LCOE), and maximal reduction in eCO_2 . The analysis yielded insights into the system's output energy capacity, its associated electrical energy costs, and the extent of carbon emissions reduction achieved.

The research gap addressed in this study lies in the application of the PSO and GWO algorithms to optimize three key parameters: E_{out} , LCOE, and eCO_2 . In contrast, the previous study used HOMER 3.14 software for techno-economic analysis, while the other used SAM software [16–18].

Implementing PSO and GWO algorithms in Python is expected to significantly contribute to finding the optimal values of techno-economic analysis parameters. In this study, the application of these methods contributes to

achieving an average Eout of 207,314.31 kWh, an average LCOE of IDR 952.274 kWh, and an average eCO₂ of 428,975.44 kgCO₂e.

As of April 2024, there are 1,380 Public Electric Vehicle Charging Stations (SPKLU) in Indonesia [19], with only 54 units located on Kalimantan Island. Given the island's average solar irradiation of 4.5863 kWh/m², there is significant potential to harness solar energy as a primary source for EV chargers. This could increase the number of electric vehicles charging stations on Kalimantan Island, particularly those utilizing green energy sources.

This study introduces a novel application of PSO and GWO algorithms to optimize PV-based electric vehicle charging systems across 11 cities in Kalimantan, Indonesia. The proposed approach offers enhanced solutions for achieving three critical objectives: maximizing Eout, minimizing LCOE, and maximizing eCO₂. This comprehensive multi-objective optimization in the context of Kalimantan's diverse geographic conditions represents a significant advancement in the field, addressing a research gap in the optimization of renewable energy systems for electric vehicle infrastructure in emerging markets.

1 Related works

Numerous scholarly inquiries have addressed the techno-economic examination of EV charging stations powered by solar PV systems. For instance, in [20], the amalgamation of EVs and PV systems within the electricity distribution infrastructure is witnessing a rise owing to environmental apprehensions and the diminishing reliance on fossil fuels [21]. However, this integration encounters irregular power demands and fluctuating loading conditions [22], necessitating proficient control strategies and scheduling mechanisms [23]. This research proposes a solar-based grid-tied charging station (SGTCS) to optimize EV charging through scheduling. The research utilizes HOMER Grid with a case study in Islamabad that includes estimating annual cost, energy cost, EV scheduling, grid power usage reduction, and environmental impact.

In [24], the escalating costs associated with fossil fuels within the transportation sector may exacerbate concerns regarding fossil fuel depletion and environmental emissions, thereby fostering the adoption of EVs and necessitating the establishment of readily accessible charging infrastructure. This study analyzes the design and performance of utilizing the rooftop of a fueling station to become a GCPV in Pakistan. Design an EVCS and compare its techno-economic performance using the SAM.

The study [25] examines the technical and economic viability of implementing a hybrid power system integrating PV and WT technologies to facilitate environmentally sustainable electric vehicle charging infrastructure across five sites in China. Using HOMER Pro 3.14, the optimal

charging station scheme was identified. The results show that PV/WT/battery hybrid stations are the best solution, with Nanjing City being the most economical and Zhengzhou the least. These stations can meet current charging demands, although sensitivity analysis suggests that increasing the load or the number of EVs will reduce their performance. Balancing the number of EVs can improve station economy and performance.

In [26], this research assessed the techno-economic and environmental ramifications of solar photovoltaic power generation for electricity and hydrogen production across five urban centers in India. The hydrogen produced was capable of filling 20 hydrogen vehicles at each location. The results show Kolkata has the highest hydrogen production (82,054 kg/year), and Mumbai has the lowest hydrogen cost (\$3.00/kg). The aggregate electricity production across all urban areas amounts to 25 GWh annually, resulting in a yearly reduction of 20,744 metric tons of CO₂ emissions. In comparison, there exists a potential for a further reduction of 2,453 tons per year through transitioning from gasoline to hydrogen utilization.

2 Method

This research focuses on optimizing PV EV charger systems using a combination of PSO and GWO algorithms to achieve maximum energy output, cost reduction, and lower carbon emissions. The charging station includes two spots, each with a 22 kW capacity, ensuring full daily charging. The study was carried out in 10 major cities across Kalimantan and Ibu Kota Nusantara (IKN). By integrating these advanced algorithms, this approach significantly improves the efficiency of PV system optimization, particularly in regions with high solar potential, surpassing traditional software-based methods.

In Fig. 1, there is a system circuit diagram of the PV EV charger system, which contains a solar system, an energy storage system in the form of a battery, an inverter as a DC to-AC converter, and a load in the form of an EV charger and is connected to the electrical grid. To get the optimal values of Eout, LCOE, and carbon emissions, PSO and GWO algorithms will be used.

Fig. 2 presents the graphical abstract of the techno-economic model for PV-based EV charging, optimized using PSO and GWO in Kalimantan, along with a comparison of ROI across different electricity tariffs and optimization of charging locations in Samarinda.

Table 1 below presents the specifications of the main components used in the PV system, including photovoltaic modules, the inverter, and the battery. These parameters include the power output, voltage, current, efficiency, and pricing for different configurations of each component, providing an overview of the technical and economic characteristics essential for system design and analysis.

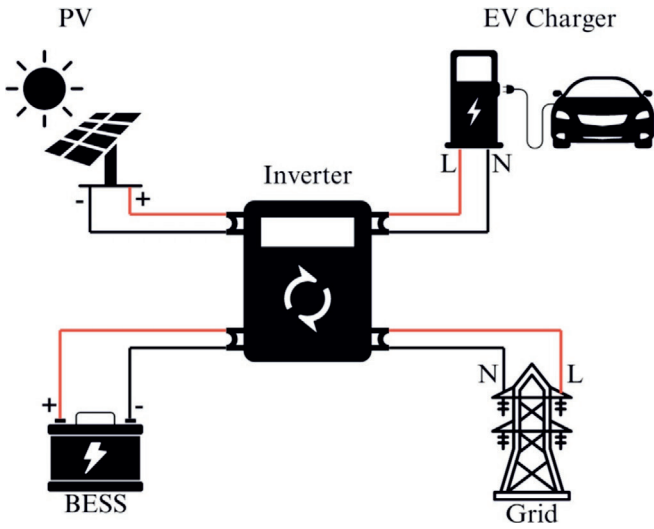


Fig. 1. System circuit diagram.

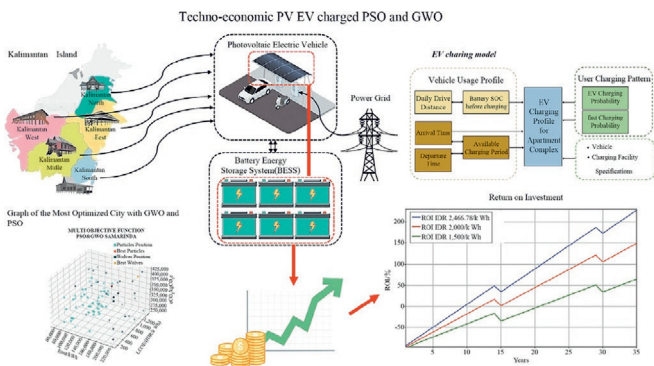


Fig. 2. Graphical abstract diagram.

The specifications outlined in Table 1 provide a comprehensive overview of the key components required for the PV system [27–29]. By comparing different configurations, it becomes easier to select the most appropriate components based on system requirements, performance, and cost, ensuring an optimal balance between efficiency and affordability in the overall design.

2.1 Technical analysis

- 1) *Electrical energy requirements*, in technical planning, the electrical tolerance load is 25 %–40 % greater than the load value used to be able to avoid increasing the electrical load on the system [30]. Electrical energy requirements can be calculated using the following equation:

$$W_s = W_d + (W_d \times S_F) \tag{1}$$

W_s is the planned electrical energy supply requirement, W_d is the electrical energy required daily, and S_F is the safety factor or electrical energy tolerance.

Load Constraints:

- The system’s electrical load, specifically the EV charger, is limited by the charging capacity (22 kW) and operating hours (17 h/day). The system must avoid exceeding these operational limits to prevent overloading the grid and ensure efficient operation.

Grid Interaction Constraints:

- For grid-tied systems, operational constraints are necessary to manage the power exchange with the grid. This includes limiting the maximum export and import power to prevent grid instability.

- 2) *Solar panels*, Solar cells, which are fabricated from semiconductor materials, have the capability to convert solar radiation into electrical energy [31]. This conversion process is essential for harnessing renewable energy from the sun [32]. Solar panels have several types that are distinguished based on the material they are made of, one of which is monocrystalline which has an efficiency of between 19 %–25 % [33–36]. To determine the PV capacity necessities and the quantity of PV modules can be computed utilizing the subsequent equation [37]:

$$P_{PLTS} = \frac{W_s}{G} + \left(L_{\text{losses}} \times \frac{W_s}{G} \right) \tag{2}$$

where P_{PLTS} is the peak power capacity of the solar power plant, W_s is the total energy required, and G is the average solar irradiation at the location.

Table 1
Components specification.

Components	Parameters	Specification		
		655 Wp	500 Wp	400 Wp
PV	Pmax	655 W	500 W	400 W
	Voc	45.2 V	51.5 V	37.07 V
	Isc	18.43 A	12.13 A	13.79 A
	Vmp	38.1 V	43.4 V	31.01 V
	Imp	17.20 A	11.53 A	12.9 A
	η	21.1 %	20.7 %	20 %
	Price	IDR	IDR	IDR
Inverter	Pin	5,132,000	3,576,975	1,909,200
	Power Factor	0.8		
	η	97.6 %		
Battery	Price	IDR 56,593,670		
	Rated capacity	100 Ah		
	Nominal voltage	48 V		
	Price	IDR 106,500		

The quantity of energy produced by the system, which is influenced by solar irradiation, can be ascertained using the equation provided in references [38,39]:

$$E_{\text{out}} = N_{\text{PV}} \times A_{\text{PV}} \times \eta_{\text{PV}} \times G \quad (3)$$

E_{out} represents the output energy of the system, with N_{PV} denoting the quantity of PV modules, A_{PV} representing the area of the PV modules, η_{PV} indicating the panel's efficiency, and G symbolizing solar irradiation.

PV System Constraints:

- The PV system's peak power production is constrained by solar irradiance, which varies by location and time of day. Irradiation data from Global Solar Atlas was used, but the system must also factor in operational inefficiencies due to ambient temperature changes.
- Another constraint is related to the inverter capacity, which must be larger than the maximum load to prevent system overloading. This paper calculates a 25 % tolerance on the inverter size.
- 3) *Inverter*, inverter functions as a crucial device within the system, capable of converting DC into AC. This transformation is achieved through a process of filtration and the generation of a sinusoidal signal, ensuring that the electrical output is compatible with standard AC systems [40,41]. The capacity of the inverter within the system can be calculated using the following equation:

$$P_{\text{inv}} = P_{\text{d}} \times \eta_{\text{inv}} + (P_{\text{d}} \times S_{\text{F}} \times \eta_{\text{inv}}) \quad (4)$$

P_{inv} is the required inverter power, P_{d} is the load power used, and η_{inv} is the inverter's efficiency.

- 4) *Battery Energy Storage System (BESS)*, BESS is crucial for RE systems due to their susceptibility to climate and weather variations. Thus, ensuring effective and stable energy utilization necessitates the provision of a storage system [42]. However, the DoD principle limits battery usage to 80 % capacity, with the remaining 20 % termed as SoC [43,44]. The following equation can determine the calculation of battery capacity:

$$C_{\text{Tbatt}} = \frac{N_{\text{OD}} \times W_{\text{L}}}{D_{\text{DoD}} \times \eta_{\text{batt}}} \quad (5)$$

$$I_{\text{Cbatt}} = \frac{C_{\text{tbatt}}}{V_{\text{batt}}} \quad (6)$$

where C_{Tbatt} is the total battery capacity, D_{DoD} is the Depth of Discharge, η_{batt} is the battery efficiency, I_{Tbatt} is the total battery current, V_{batt} is the battery voltage, and N_{OD} is the number of autonomous battery days.

Battery Constraints:

- The BESS operates with a D_{DoD} of 85 % to maintain its longevity and efficiency. The SoC should not drop below this threshold to avoid system failures.
- The battery charging and discharging rates must also be constrained to prevent overheating or overcharging, which could damage the storage unit.

2.2 Economic analysis

Economic and environmental constraints are critical factors in determining the feasibility and sustainability of the system. These constraints guide the system's financial and ecological performance, ensuring that it operates within acceptable limits while providing economic benefits and minimizing environmental harm. Economic constraints pertain to the financial metrics that assess the system's cost-efficiency, while environmental constraints focus on the system's impact on carbon emissions and its contribution to sustainability efforts. Together, these constraints form a comprehensive framework that balances economic viability with environmental responsibility, ensuring the system meets financial and ecological goals. Economic and Environmental Constraints:

- In terms of economic constraints, the cost-effectiveness of the system is evaluated based on the payback period and NPV, while environmental constraints focus on the maximum carbon emission reductions achievable through optimal system configurations.
- 1) Net Present Value (NPV), It is a crucial metric in investment analysis used to assess a project's financial viability and profitability. It is determined by summing all expected cash inflows and outflows throughout the project's duration, accounting for the time value of money. A positive NPV indicates that the project will likely generate more income than costs, making it profitable. In contrast, a negative NPV suggests that the fees exceed the benefits, making the project financially unviable. This makes NPV an essential tool for evaluating long-term investments [45]. The following equation can determine the NPV value [46–50]:

$$V_{\text{NPC}} = -C_{\text{APEX}} + \sum_{t=1}^N \frac{C_{\text{F},N}}{(1+r)^t} \quad (7)$$

NPV represents the Net Present Value, C_{APEX} denotes the capital expenditure, $C_{\text{F},N}$ signifies the cash flow, N refers to the project's lifespan, and r is the discount rate.

2) *Payback Period* (P_P), P_P measures the duration required for a project to recoup its initial capital investment through cash inflows or revenues [51,52]. P_P can be calculated using the following equation:

$$P_P = \frac{C_{APEX}}{R} \quad (8)$$

with P_P as the Payback Period, C_{APEX} as the cost of capital used, and R being revenue or income.

3) *Levelized Cost of Energy* ($LCOE$), $LCOE$ represents the cost of electrical energy over the entire lifespan of a project and is typically used to evaluate the feasibility and competitiveness of the project. It encompasses all expenses related to constructing, operating, and maintaining the energy generation system [53]. To determine the $LCOE$ value, we can use the equation [54,55]:

$$C_{LCOE} = \frac{C_{APEX} + \sum_{t=1}^N \frac{C_t}{(1+r)^t}}{\sum_{t=1}^N \frac{E_t}{(1+r)^t}} \quad (9)$$

C_{LCOE} is the Levelized Cost of Energy, C_{APEX} is the cost of capital spent, C_t is the total outgoing costs in year t , r is the discounted ratio, and E_t is the energy produced at time t .

2.3 Environmental analysis

1) *Carbon Emissions*, carbon emissions are exhaust gasses produced by conventional power generation systems and conventional transportation systems, and these emissions can significantly worsen air quality and contribute to environmental degradation [56]. To calculate the amount of carbon emissions produced by the generating system, we can use the equation [57,58,59]:

$$E_{CO_2} = E_p \times E_f \quad (10)$$

from the equation, E_{CO_2} represents the carbon emission, E_p denotes the energy produced, and E_f is the carbon emission factor, valued at 0.757 kgCO₂e kWh [60].

2.4 Objective function

1) Multi-Objective Optimization

In this study, a multi-objective optimization approach is used to optimize the performance of the PV EV charger system based on three main objectives: output E_{out} , $LCOE$ minimization, and eCO₂. Using two optimization algorithms, PSO and GWO, allows for achieving a balanced optimal solution for all three objectives.

a) *Output Energy Maximization* (EOM): The first objective is to maximize the energy generated by the PV system to ensure that the system can supply enough power to operate the EV charging station [61]. This objective function considers the average solar radiation at the study site, the efficiency of the solar panels, and the configuration of the Battery energy storage system (BESS).

Objective function:

$$\text{Maximize } E_{out} = \eta_{PV} \times N_{PV} \times A_{PV} \times G \quad (11)$$

Where:

η_{PV} = SolarPanelEfficiency

N_{PV} = Number of PV Modules

A_{PV} = PV Module Area

G = Solar Radiation

b) *Minimization of Levelized Cost of Energy* ($LCOE$): $LCOE$ measures the overall cost of energy production over the lifetime of the system. It optimizes the capital cost (CAPEX), operation and maintenance cost (OPEX), and the amount of energy produced by the system in a given time period [62]. This objective is designed to achieve the least possible energy cost, thereby improving the economic viability of the project.

Objective function:

$$\text{Minimize } LCOE = \frac{C_{APEX} + \sum C_{OPEX,t}}{\sum E_t} \quad (12)$$

Where:

C_{APEX} = Cost of Capital $C_{OPEX,t}$ = Operational and Maintenance Cost Per Year

E_t = Energy Produced in Year t

c) *Carbon Emission Reduction Maximization* (eCO₂): This objective function aims to maximize the reduction of CO₂ emissions by utilizing renewable energy sources, such as solar power, instead of fossil fuels. This function calculates how much CO₂ can be avoided with the use of renewable energy systems.

Objective function:

$$\text{Maximize } eCO_2 = E_{out} \times E_f \quad (13)$$

Where:

E_{out} = Energy Generated by The System.

E_f = Carbon Emission Factor of Conventional Energy (kg CO₂/kWh).

This research uses PSO and GWO algorithms that are used to determine the right combination of peak power capacity from the optimal number of solar panels and bat-

teries. To obtain the maximum output energy E_{out} value, minimum energy cost LCOE, and maximum carbon emission E_{CO_2} reduction. Therefore, the objective function to be achieved in this research is as follows:

$$(a \times (N_{PV} \times A_{PV} \times \eta_{PV} \times G)) - \left(\beta \times \left(\frac{C_{APEX} + \sum_{t=1}^N \frac{C_t}{(1+r)^t}}{\sum_{t=1}^N \frac{E_t}{(1+r)^t}} \right) \right) + (\delta \times (E_p \times E_f)) \quad (14)$$

$$\text{Subject to } \begin{cases} N_{PV} \leq 164 \\ N_{batt} \leq 70 \\ E_{PV} \geq \text{Energy needed} \\ C_{LCOE_{PLTS}} < C_{LCOE_{sPKLU}} \\ E_{CO_2_{PLTS}} > E_{CO_2_{Grid}} \end{cases} \quad (15)$$

2.5 Research location conditions

This study focuses on 11 major cities in Kalimantan, including Banjarmasin, Balikpapan, Pontianak, Samarinda, Palangka Raya, and IKN, chosen for their high solar energy potential and average solar irradiation. Irradiation data was sourced from the Global Solar Atlas. Fig. 3.

In Fig. 3, the irradiation values at the research location exhibit diverse differences, with the highest irradiation located in Tarakan, which has an irradiation value of 1,737 kWh/m²/year, while the lowest irradiation value is found in Samarinda, with a value of 1,571.7 kWh/m²/year.

Table 2 provides the coordinates of each research location along with the corresponding daily and annual irradiation data. Across the 11 locations, the average daily irradiation is 4.5863 kWh/m², while the average annual irradiation is 1,674 kWh/m².

The clearness index used in the Liu-Jordan-Klein model to quantify solar irradiance reaching the Earth’s surface from the top of the atmosphere, ranges from 0 to 1. A value of 1 signifies no loss in irradiance (all insolation is direct beam), while 0 indicates complete cloud cover with no irradiance [63,64].

Fig. 4 presents the clearness index ratio for each of the 11 research locations, with an average of 0.5058. This value indicates that the research sites experience slightly cloudy skies but remain highly suitable for solar panel installation [54].

The efficiency of PV systems is also impacted by ambient temperature, decreasing by 0.4 % to 0.65 % for each 1 °C increase above the Standard Test Condition (STC) temperature of 25 °C [43,65].

Fig. 5 presents a monthly ambient temperature graph for each research location. Across the 11 sites studied, the average ambient temperature ranges from 26.8 °C to 27.3 °C, which is considered favorable for optimizing PV efficiency [66]. Additionally, the figure highlights increase in ambient temperature during May and October at all locations.

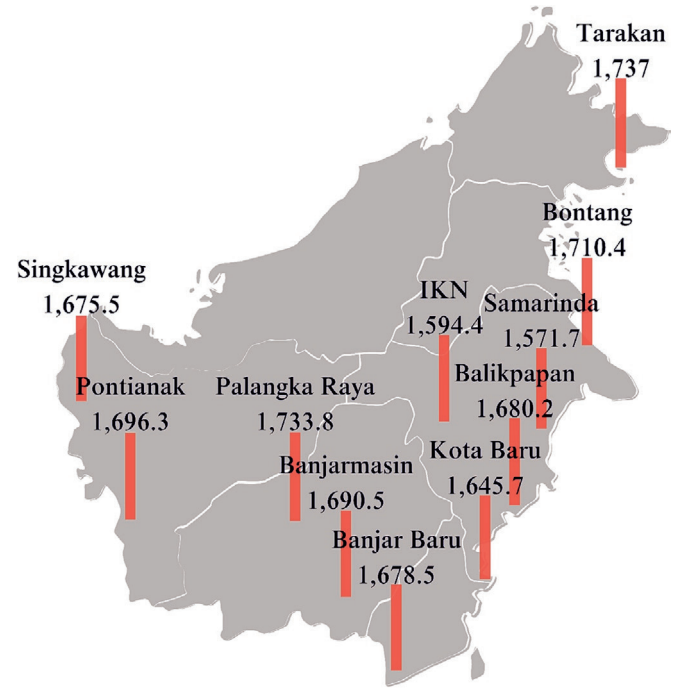


Fig. 3. Annual solar irradiation data on 11 research locations/(kWh/m²).

2.6 Annual load forecasting

This section presents the annual load forecasting for the PV EV charger, which has a maximum charging capacity of 22 kW across two points and operates 17 h daily from 7:00 to 24:00. Assuming full capacity, the station can meet a monthly load of approximately 22,440 kWh. However, daily usage varies, influenced by holiday seasons in June-July and December-January. The annual load forecast is depicted in Fig. 6.

3 Results and discussion

3.1 Technical analysis

- 1) *Charging station electrical energy requirements*, in this study, the charging station is designed with a power rating of 22 kW per charging point. With two charging points operating simultaneously, the station can deliver a total of 44 kW per hour. Charging stations will be installed in shopping centers (malls) where charging stations can operate from 7 am to 12 pm (17 h), so the daily energy used per point is 374,000 Wh or 374 kWh. With (1), the value of the electrical energy requirement W_s is 486,200 Wh.
- 2) *The capacity of solar power plant*, in this research, the solar power plant is designed to supply the load for 6 h daily, from 9:00 to 15:00 per charging point. Thus, the energy requirement for this 6-hour is

Table 2
Site coordinates and irradiation data.

Cities	Location Coordinates	Daily Irradiation/(kWh/m ² /day)	Annual Irradiation/(kWh/m ² /year)
Banjarmasin	−03.2975°, 114.585278°	4.632	1,690.5
Balikpapan	−01.275°, 116.856111°	4.603	1,680.2
Pontianak	00.000556°, 109.322222°	4.647	1,696.3
Samarinda	−00.526667°, 117.115278°	4.306	1,571.7
Palangka Raya	−02.207222°, 113.916389°	4.75	1,733.8
Tarakan	03.3°, 117.633056°	4.759	1,737
Banjarbaru	−03.42509°, 114.87998°	4.599	1,678.5
Singkawang	00.906944°, 108.988889°	4.59	1,675.5
Bontang	00.123611°, 117.471667°	4.686	1,710.4
Kota Baru	−02.795°, 115.971389°	4.509	1,645.7
IKN	−00.973889°, 116.701667°	4.368	1,594.4

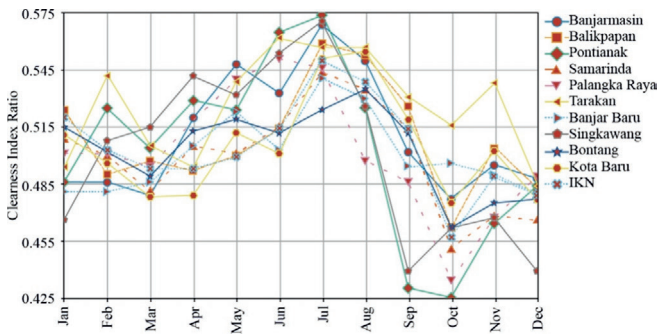


Fig. 4. Monthly ambient clearness index of each locations.

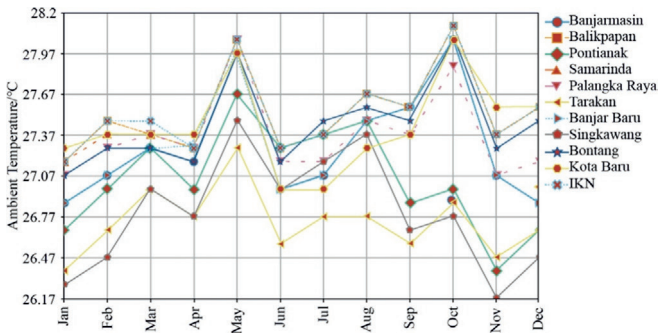


Fig. 5. Monthly ambient temperature.

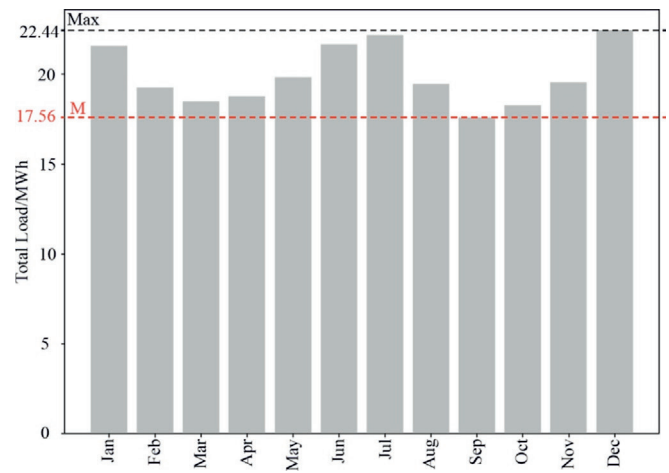


Fig. 6. Annual load forecasting.

In this research, the battery used is LiFePo₄ type which has a DoD of 85 % and an efficiency of 98 %. Thus with (5) the capacity of the battery per point C_{Tbatt} is 165,066 Wh, and with (6) the current capacity of the battery per point I_{Cbatt} is 3,438.875 Ah.

3.2 System optimization results

In this research, advanced optimization algorithms are utilized to achieve three primary objectives, that is maximizing the system’s output energy, minimizing energy costs, and maximizing the reduction in carbon emissions. Specifically, PSO and GWO algorithms have been selected for their robustness and efficiency in handling complex optimization problems. These are implemented in Python to identify the optimal values for the three objective functions.

To comprehensively assess the performance of the two optimization algorithms, this study conducts a detailed comparison of the results obtained from the PSO and GWO algorithms. The simulation outcomes for both algorithms are systematically analyzed and presented in Table 3, highlighting the relative effectiveness and effi-

132,000 Wh. With (1), the electrical energy requirement electrical energy requirement for PV W_{sPV} is 171,600 Wh. Among the 11 research locations, the average solar irradiation is 4.5863 kWh/m². Then with (2), the capacity of solar power plant P_{PVt} per point is 45 kWp.

3) *Inverter capacity*, in this study, the tolerance used to perform the calculation is 20 % with an inverter efficiency of 95 %. So, with (4) the inverter capacity P_{inv} is 25 kW.

4) *Battery energy requirements*, in this study, the battery acts as an energy storage component that will supply the load for 5 h, starting at 15:00 to 20:00. By using a safety factor of 25 %, with (1) the electrical energy requirement for battery W_{sbatt} is 137,500 Wh.

Table 3
Simulation result data.

Algorithms	Max Iter	P_{PV}/Wp	N_{PV}/pcs	I_{Cbat}/Ah	N_{bat}/pcs	E_{out}/kWh	LCOE/(IDR/kWh)	$eCO_2/(kgCO_2e)$
Banjarmasin								
PSO	150	655	138	100	70	144,919.13	942.13	364,055.78
GWO	150	655	138	100	70	206,459.97	1,001.79	423,513.76
CPSO	150	655	138	100	70	152,305.68	989.257	379,263.49
Balikpapan								
PSO	150	655	138	100	70	144,036.15	947.9	363,387.37
GWO	150	655	138	100	70	208,748.05	1,007.94	430,542.27
CPSO	150	655	138	100	70	150,873.54	995.34	381,564.89
Pontianak								
PSO	150	655	138	100	70	145,416.34	938.9	364,432.17
GWO	150	655	138	100	70	210,748.31	998.37	432,056.47
CPSO	150	655	138	100	70	152,678.51	985.67	381,654.83
Samarinda								
PSO	150	655	138	100	70	134,734.93	1,013.34	356,346.34
GWO	150	655	138	100	70	195,268.008	1,077.52	420,337.88
CPSO	150	655	138	100	70	142,542.68	1,063.86	371,564.72
Palangka Raya								
PSO	150	655	138	100	70	148,631.05	918.59	366,865.7
GWO	150	655	138	100	70	215,407.31	976.78	435,583.34
CPSO	150	655	138	100	70	156,782.41	961.23	382,691.98
Tarakan								
PSO	150	655	138	100	70	148,905.37	916.9	367,073.36
GWO	150	655	138	100	70	215,804.88	974.98	435,884.29
CPSO	150	655	138	100	70	156,850.29	955.32	382,926.49
Banjar Baru								
PSO	150	655	138	100	70	143,890.42	948.86	363,277.05
GWO	150	655	138	100	70	208,536.84	1,008.96	430,382.39
CPSO	150	655	138	100	70	150,945.89	991.54	381,789.39
Singkawang								
PSO	150	655	138	100	70	143,633.24	950.56	363,082.36
GWO	150	655	138	100	70	208,164.12	1,010.77	430,100.24
CPSO	150	655	138	100	70	150,795.51	997.97	378,456.12
Bontang								
PSO	150	655	138	100	70	146,625.07	931.16	365,347.18
GWO	150	655	138	100	70	212,500.09	990.14	433,382.57
CPSO	150	655	138	100	70	153,928.46	977.22	383,614.94
Kota Baru								
PSO	150	655	138	100	70	141,078.62	967.77	361,148.52
GWO	150	655	138	100	70	200,731.57	1,029.07	424,473.8
CPSO	150	655	138	100	70	148,835.43	1,015.63	378,206.95
IKN								
PSO	150	655	138	100	70	136,680.89	998.91	357,819.44
GWO	150	655	138	100	70	198,088.26	1,062.18	422,472.8
CPSO	150	655	138	100	70	143,512.85	1,045.86	375,860.91

ciency of each algorithm in optimizing the parameters of the system under study.

The data presents a comparative analysis of different optimization algorithms (PSO, GWO, CPSO) applied to a PV-based EV charger system with a BESS across various locations in Kalimantan. The parameters, such as PV capacity and number of batteries, remain constant across all scenarios to ensure a fair comparison. GWO consistently delivers the highest energy output (Eout), with figures ranging from 195,268.008 kWh in Samarinda to 215,804.88 kWh in Tarakan, outperforming PSO and CPSO. However, this high energy yield comes at a cost,

as GWO is often associated with a higher Levelized Cost of Energy (LCOE).

The data reveals that GWO consistently achieves higher CO₂ emissions reductions than the other algorithms, indicating better overall energy performance. For instance, in Banjarmasin, GWO results in 423,513.76 kgCO₂e emissions, significantly higher than PSO's 364,055.78 kgCO₂e. This trend is evident across multiple locations, such as Balikpapan and Pontianak, where GWO outperforms PSO and CPSO in reducing CO₂ emissions by generating more clean energy. Therefore, GWO is more effective at reducing reliance on conventional energy sources and mit-

igating emissions, making it the best choice for projects focused on maximizing environmental benefits.

On the other hand, PSO emerges as the most cost-effective algorithm, consistently providing the lowest LCOE across most regions, such as 995.34 IDR/kWh in Balikpapan and 985.67 IDR/kWh in Pontianak. This makes PSO the preferred choice for projects prioritizing cost efficiency. CPSO, meanwhile, sits in the middle, delivering moderate performance in terms of cost. While it does not achieve the lowest LCOE, it offers a balanced alternative between cost-effectiveness and system performance across various locations.

Based on the simulation results, GWO produces higher energy output (Eout) in most locations. This signifies that GWO is more effective in optimizing energy production in areas with high solar energy potential, such as Tarakan, which has the highest annual irradiation of 1,737 kWh/m²/year. However, this GWO has a higher LCOE than PSO, which means that the use of GWO may be less economical if the main goal is to minimize energy costs.

The study reveals significant geographic variations in system performance across different cities, with lower irradiation areas like Samarinda (1,571.7 kWh/m²/year) yielding reduced energy output and higher energy costs for both PSO and GWO algorithms, underscoring the critical importance of solar potential assessment in project planning; conversely, locations such as Tarakan demonstrate optimal conditions for PV system implementation due to higher irradiation levels, resulting in increased energy output and lower energy costs.

Fig. 7 the simulation results present a comparison between the most and least optimal cities identified in

the study. Tarakan, with an annual solar irradiation of 1,737 kWh/m², stands out as the most optimal location. This high irradiation level enables Tarakan to produce 215,804.88 kWh of energy at a notably low cost of IDR 916.9/kWh. Furthermore, Tarakan achieves a substantial reduction in carbon emissions, totaling 435,884.29 kgCO₂-e. These results underscore Tarakan’s exceptional suitability for PV system implementation, making it the most favorable site in the study based on both cost-efficiency and environmental impact.

In the other hand, Samarinda, with the lowest annual irradiation of 1,571.7 kWh/m², was determined to be the least optimal location for this research. It is only able to produce 195,268.01 kWh of energy, with an energy cost of IDR 1,013.34/kWh, and can reduce carbon emissions by only 420,337.88 kgCO₂e.

3.3 Economic analysis

Using sales data based on Fig. 6, this study’s economic analysis encompasses three scenarios distinguished by variations in the selling price of electricity per kWh. To be competitive with PLN’s SPKLU, the charging tariff in this system start from IDR 2,466.78 kWh (equivalent to the SPKLU tariff), IDR 2,000 kWh, and IDR 1,500 kWh.

- 1) *Net Present Value (NPV)*, with the difference in electricity sales tariffs, 3 NPV results will be obtained. Fig. 8 is the net cash flow during the project period. From the 3 scenarios, it can be seen that the tariff of IDR 2,466.78/kWh has a greater annual income when compared to the other 2 scenarios. However,

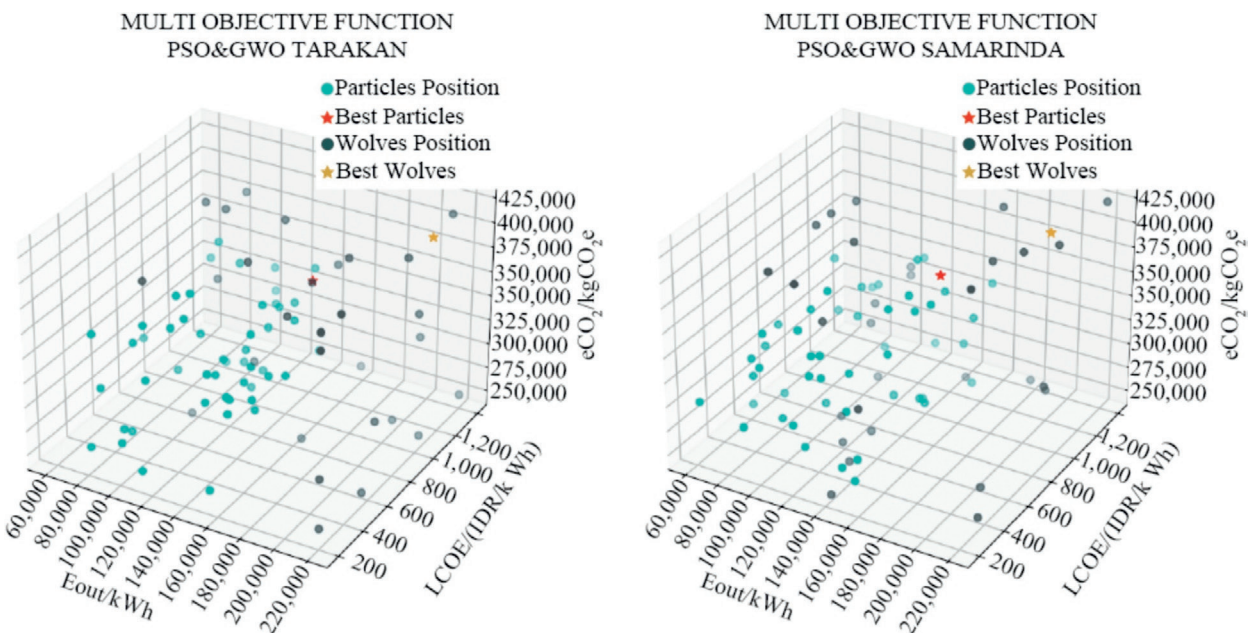


Fig. 7. Graph of the most optimized and least optimized city.

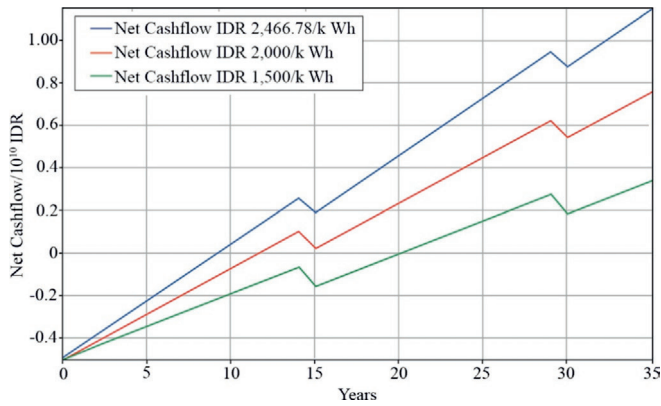


Fig. 8. Net cashflow graph.

the tariff will have the same sales tariff as SPKLU, therefore it would be better to use a sales tariff of IDR 2,000/kWh because the amount of income earned is still more when compared to a sales tariff of IDR 2,500/kWh. In all three scenarios there is a decrease in cash flow in the 15 th and 30 th years, the decrease is due to the replacement of several components in the system.

Fig. 9 The NPV graph for the project period highlights the financial outcomes of each scenario. Scenarios 1 and 2 yield positive NPVs, with Scenario 1 reaching IDR 1,730,306,227.06 and Scenario 2 achieving IDR 194,567,379.62, indicating profitability for both. In contrast, Scenario 3, with a sales tariff of IDR 1,500/kWh, results in a negative NPV of -IDR 1,450,467,591.30, signifying financial loss. Consequently, Scenarios 1 and 2 are deemed economically viable, whereas Scenario 3 is considered unfeasible due to its negative return.

2) *Payback Period (PP)*, PP has a correlation with Return on Investment (ROI), so determining PP

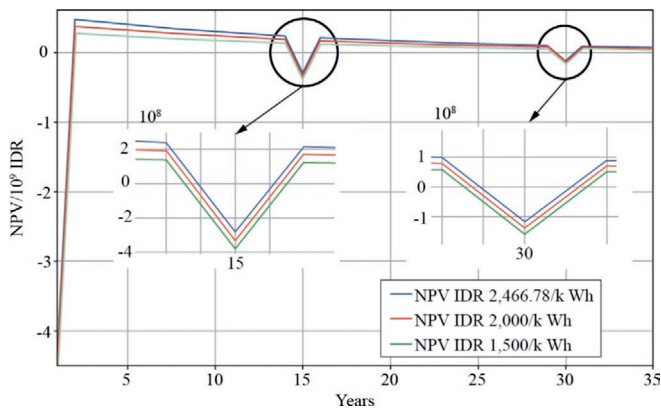


Fig. 9. Net present value (NPV) graph.

can be seen by using the ROI graph. Fig. 10 is a graphic image of ROI from the three scenarios that have been made, from the three scenarios have different ROI values. The ROI value passed the 0-point indicating that the project had reached the PP stage. In scenario 1, PP is obtained at 9.22 years or around 9 years and 2 months, then in the second scenario, PP is reached at 11.62 years or about 11 years and 7 months, while for the third scenario, it can reach PP at the 20 th year. However, because the NPV value in the third scenario is negative, the project with the third scenario is not profitable to do.

The simulation results demonstrate that a positive NPV is achievable only with elevated electricity tariffs of IDR 2,466.8/kWh or IDR 2,000/kWh, while lower tariff scenarios, such as IDR 1,500/kWh, yield negative NPVs, indicating project unprofitability; these findings underscore the critical importance of designing supportive tariff policies to ensure the economic viability of PV projects, particularly in regions with high solar energy potential.

The analysis reveals significant sensitivity of the system to electricity tariffs, with lower rates directly impacting project profitability, as evidenced by extended PP at reduced tariffs; this finding underscores the necessity for a more supportive tariff structure within energy policy frameworks to accelerate the adoption of PV-based EV charging infrastructure.

The PSO-GWO hybrid optimization enhances energy output while reducing costs and emissions, with Tarakan showing optimal results. This approach outperforms previous studies and provides new insights for solar-based EV charging station site selection across varied geographic locations.

This research has several limitations that need to be considered. Geographically, the study focused on 11 cities in Kalimantan, including the Capital City of the Archipelago (IKN), with high solar energy potential. The results

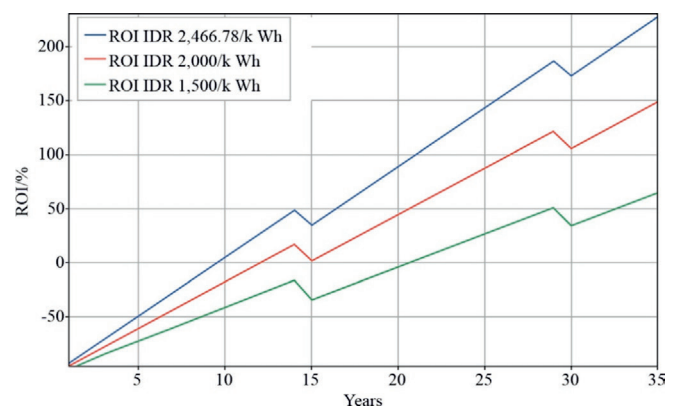


Fig. 10. Return of investment (ROI) graph.

may only be partially relevant for other regions with different geographical conditions, climates, or solar irradiation levels. The irradiation data comes from the Global Solar Atlas and reflects annual averages, so seasonal variations should be captured in detail.

Regarding technology, the research uses monocrystalline solar panels with specific efficiencies (19–25 %) and LiFePo₄ batteries with particular capacities. The system performance may differ if other technologies, such as solar panels with higher efficiencies or alternative battery types, are used. Due to their effectiveness, PSO and GWO algorithms were chosen for the optimization approach. Still, they were not compared directly with other algorithms, such as genetic algorithm (GA) or ant colony optimization (ACO). The optimization results are also affected by the initial parameters and simulation constraints. Economically, the analysis is based on three electricity tariff scenarios (IDR 2,466.78/kWh, IDR 2,000/kWh, and IDR 1,500/kWh), which may not reflect future changes in tariffs or incentives.

External factors such as inflation and rising maintenance costs are also not considered. In addition, load utilization patterns were assumed to be constant for the two electric vehicle charging points (22 kW per point) without considering variations in utilization patterns at certain times or seasons. Other limitations include irradiation data representing site averages without considering microclimatic variations and reliance on historical data-based simulations without direct field measurements. From an environmental perspective, the carbon emission reduction analysis was based solely on a standard factor (0.757 kgCO₂/kWh) without including a life cycle analysis of the technology used. With these limitations, the research results still provide important insights for developing PV-based electric vehicle charging systems in Kalimantan. However, further validation is required for applications in different locations or conditions.

4 Conclusion

This research successfully conducted technical, economic, and environmental analyses of PV-based electric vehicle charging systems in 11 cities in Kalimantan. The study used PSO and GWO algorithms to identify the optimal capacity of solar panels (45 kWp per point) and batteries (70 48 V 100 Ah units). Results show that the system is capable of producing 195,268.008 kWh to 215,804.88 kWh of energy, with energy costs ranging from IDR 916.9/kWh to IDR 1,013.34/kWh, and reducing carbon emissions by 435,884.29 kgCO₂e. This study provides a new contribution to science, particularly in renewable energy system optimization for electric vehicle charging stations. The application of PSO and GWO algorithms has proven its superiority in achieving multiobjective opti-

mization, including increasing energy output, reducing energy costs, and reducing carbon emissions. Compared to previous methods, such as HOMER and SAM, this approach offers a more accurate and efficient solution, especially for diverse geographical conditions such as in Kalimantan. The results of this study support the development of renewable energy-based electric vehicle charging infrastructure in regions with high solar energy potential, such as Kalimantan. Tarakan, as the location with the highest annual irradiation, stands out as the optimal location for PV system implementation, while Samarinda faces more significant challenges due to lower irradiation levels. This research is relevant to developing renewable energy-based charging infrastructure in Indonesia. Still, it can also serve as a reference for other developing countries facing similar challenges. Thus, this study contributes to the scientific literature and supports global environmental sustainability goals.

CRedit authorship contribution statement

Aripriharta: Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Satria Adiguna:** Writing – original draft, Visualization, Software, Project administration. **Arif N. Afandi:** Resources, Project administration, Methodology. **Muhammad Cahyo Bagaskoro:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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