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Article

Harnessing wind and solar power for electric vehicle charging: a feasibility study at Ikas supermarket, Lefkosa, Northern Cyprus

Youssef Kassem[1,2,3]*, Hüseyin Çamur [1], Ahmad Hussein[1]

[1]Department of Mechanical Engineering, Engineering Faculty, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus
[2]Energy, Environment, and Water Research Center, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus
[3]Science, Technology, Engineering Education Application, and Research Center, Near East University, 99138 Nicosia (via Mersin 10, Turkey), Cyprus

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*Corresponding author
Email address:
yousseuf.kassem@neu.edu.tr
youssef.kassem1986@hotmail.com

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ABSTRACT

Electric vehicles (EVs) have replaced conventional bio-fuel cars over the past ten years. Electric vehicles, or EVs, have become popular for both financial and environmental reasons. One of the most significant challenges facing humanity today is environmental degradation. From both an economic and ecological perspective, it would be highly beneficial if electric automobiles could be charged using renewable energy. The use of EVs in Northern Cyprus remains in its early stages. Thus, the viability of charging from renewable sources is investigated. In addition to comparing fuel-based and electric vehicles and determining the economic viability of charging using renewable sources, the study explains ways to charge electric vehicles using hybrid wind and solar power systems. The costs of the required components have been obtained from manufacturers, and the average cost is then taken into account. The results demonstrated that the developed system achieved a maximum monthly energy output of 13,500 kWh in March and ensured stable production throughout the seasons by utilizing solar and wind resources in combination. Additionally, it has the capacity to support 58 EV chargers per day, which can charge approximately 1,700 EVs per month, including the GÜNSEL B9 model. Economically, the system was extremely viable with a payback time of just 3.34 years when electricity was sold at $0.31/kWh. Moreover, the proposed system offered a significant 96% reduction in carbon emissions compared to conventional grid electricity. These results demonstrate the hybrid system's success in facilitating sustainable, high-capacity EV charging, yielding significant environmental and economic benefits. Additionally, compared to fuel vehicles, EVs are almost twice as advantageous and environmentally friendly.

1. Introduction

In response to the urgent need to mitigate the effects of climate change, nations have lately altered global transportation patterns [1, 2]. One of the prospective solutions that is gaining traction is the usage of electric vehicles (EVs), which offer a more environmentally friendly substitute for conventional internal combustion engine vehicles [4, 5]. Electric vehicles (EVs) improve air quality, reduce dependency on fossil fuels, and significantly reduce greenhouse gas (GHG) emissions [6]. Rules and incentive programs have been put in place in several countries to promote the use of renewable energy sources and ease the transition to electric vehicles [7-9]. The environmental and energy issues in Northern Cyprus, as in many developing countries, are mostly caused by rapid urbanization, expanding car ownership, and an increasing reliance on imported fossil fuels [10, 11]. One of the biggest contributors to air pollution and carbon emissions in the transportation sector is personal vehicles [12]. Transport accounts for about 24 percent of global direct CO_2 emissions from fuel combustion [13]. The economy of developing countries' economy is severely impacted by the increasing use of fossil fuel-powered automobiles due to fuel imports, volatile exchange rates, and rising energy costs, in addition to environmental issues [14, 15].

Abbreviations

EOT	Equation Of Time
EPV	The energy output of the PV system
EVs	Electric Vehicles
EWT	Wind turbine's total power output
Gb	Beam Component
Gd	Diffuse Component
GDH	Direct horizontal solar irradiance
GHG	Greenhouse Gas
Gr	Reflected Component
GSI	Incident global solar irradiance on an inclined surface
KIB-TEK	Cyprus Turkish Electricity Authority
LAT	local apparent time
LCOE	Levelized cost of energy
NASA	National Aeronautics and Space Administration
NEU	Near East University
PV	Photovoltaics
SPP	simple payback period
STC	Standard Test Conditions
VAWT	vertical axis wind turbines

Air pollution also contributes to respiratory and cardiovascular diseases, increased medical expenses, and a shorter life expectancy [16]. These factors highlight the importance of adopting a more resilient and sustainable transportation system. However, there are challenges associated with the transition to EVs that require careful planning and cooperation. Although replacing all fossil fuel-powered vehicles at once is not feasible, it makes sense and is beneficial to phase them out gradually. This transition can be aided by expanding EV infrastructure, especially by setting up a huge network of PV-powered charging stations [17-19]. Among the countries that have successfully promoted the use of EVs are the United States, China, and Germany, highlighting the importance of strong legislative frameworks, financial incentives, and public awareness initiatives [6, 20, 21].

In general, EVs powered by renewable energy are consistent with both national climate pledges and global sustainable development goals. By integrating emission-free EVs with low-carbon power generation technologies, emissions from internal combustion engine vehicles can be significantly decreased [17, 22]. Numerous studies have examined the growing use of EVs in conjunction with renewable energy sources, including solar [23, 24], wind [25-27], and hybrid systems that combine solar and wind [27-29]. Combining EVs with renewable energy sources has many important advantages. It facilitates increased penetration of renewables into the energy mix and also helps reduce energy curtailment. Additional benefits include reduced greenhouse gas emissions and lower overall energy expenditures [27]. As mentioned previously, the global transition towards sustainable transport is increasingly dependent on the development of renewable energy sources for powering electric vehicles (EVs). However, the widespread utilization of EVs remains limited, particularly in urban areas such as Lefkoşa in Northern Cyprus. The high cost of the grid (Table 1) electricity, which is regulated by the Cyprus Turkish Electricity Authority (KIB-TEK), is one of the main obstacles to the region's EV adoption. Due to the higher costs, most users cannot afford to charge EVs on the grid, which significantly limits the possibility of implementing a cleaner transportation system. Therefore, the goal of this study is to develop a hybrid model that will power cafes and EV charging stations adjacent to the İkas Supermarket on the campus of Near East University using photovoltaics (PV) and vertical-axis wind turbines (VAWT). The primary objective is to improve sustainable energy production by integrating clean and renewable energy into the transportation infrastructure. The proposed hybrid system's performance and feasibility are evaluated by a comprehensive techno-economic and environmental analysis. The innovative hybrid system design of this research, which incorporates PV and VAWT technologies into pre-existing infrastructure to guarantee effective land utilization and promote the use of clean energy, is its strongest point. For local energy supply and sustainable EV charging, it focuses on the Near East University campus. A prospective charging station powered by wind and solar is depicted in Figure 1.

Table 1. Cost of energy in Northern Cyprus

Energy consumption	Cost [TL/kWh]	Cost [USD/kWh]
0-250 kW	4.8044	0.12
251-500kW	9.9115	0.25
501-750 kW	10.6573	0.27
751-1000kW	11.5519	0.29
Greater than 1000kW	13.8069	0.35

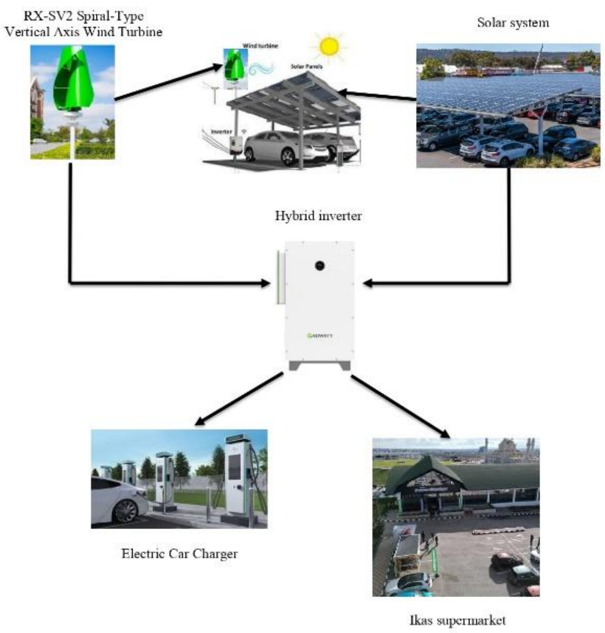

Figure 1. Prospective charging station powered by wind and solar

2. Materials and methods

2.1 Study area

The Ikas Supermarket, situated on the campus of Near East University in Lefkoşa, the capital of Northern Cyprus, was chosen as the study site. Near East University (NEU) is one of the most recognized and large universities in the region. It offers a wide range of academic programs, cutting-edge research facilities, and a strong emphasis on sustainability and technical innovation. Energy consumption is consistent and significant on campus due to the diverse student body, faculty, and staff, particularly in commercial and service sectors such as supermarkets, cafeterias, and transit hubs. Northern Cyprus, situated in the eastern Mediterranean, boasts a climate ideal for renewable energy applications, characterized by abundant sunshine throughout the year and moderate wind resources. These characteristics make the location ideal for the installation of hybrid renewable energy systems. Ikas Supermarket, a busy business center located within the university, was selected due to its advantageous location, consistent energy usage, and potential to serve as a model for integrating renewable energy in institutional settings. This site offers a practical and important context for evaluating the technical and economic feasibility of integrating PV and VAWT systems to promote sustainable energy production and reduce reliance on fossil fuels.

2.2 Dataset

One of the biggest challenges is designing solar and wind energy systems in areas lacking measurement data. It is especially challenging in Northern Cyprus due to the small number of weather stations and the lack of complete datasets. To solve this issue, satellite-derived climate datasets need to be used; however, their quality and dependability must be confirmed by comparing them to locally recorded data first. These datasets cannot be used to assess the effectiveness of wind and solar energy systems for particular areas until such validation has taken place. In this context, NASA's Earth Science Research Program is a great resource, offering a wide variety of model-based and satellite-derived products via its satellite system network. Applications for these resources are numerous and include studying climate dynamics, improving energy efficiency, and meeting agricultural needs. The initiative known as Prediction of Worldwide Energy Resources (POWER) stands out among the rest. This project provides weather and solar data from 1981 to the present on a global grid with a 0.5° × 0.5° spatial resolution. By covering regions that lack surface-based meteorological observations, the NASA POWER dataset has become a critical tool for researchers and practitioners worldwide. Furthermore, the data is freely accessible, further enhancing its utility [29].

In the literature, solar and wind energy potential was evaluated using the NASA dataset [29-34]. For instance, Kassem et al. [30] revealed that NASA provided accurate solar energy potential estimation in terms of the value of R^2, for all selected locations (Girne, Güzelyurt, Lefkoşa, and Gazimağusa). Gairaa and Bakelli [31] found a high correlation between measured data on global solar radiation and the NASA database. Arreyndip et al. [32] evaluated the feasibility of wind at different places in Cameroon based on NASA data (1983-2013) for future wind farm installation. Rafique et al. [33] evaluated the feasibility of a 100 MW grid-connected wind farm in Saudi Arabia using the NASA dataset. Gökçekuş et al. [34] utilized the NASA dataset database to investigate the distribution of wind speed at eight locations in Lebanon.

Therefore, hourly data, including solar radiation data, wind speed, and temperature for the selected location, were collected from the NASA POWER database for the period between 01-Jan to 31-Dec 2023 in this study.

2.3 Solar radiation incident on a tilted surface

Solar radiation received by a surface is composed of three main components: direct (Beam) radiation, diffuse radiation, and radiation reflected from the Earth's surface [35, 36]. These components contribute to the total solar irradiance on a tilted surface. However, due to the limited availability of measurement tools and methodologies, it is rare to find recorded data specifically for inclined surfaces [37]. This challenge necessitates the use of mathematical models to estimate the total solar irradiance on tilted surfaces based on known parameters. The incident global solar irradiance on an inclined surface (GSI) can generally be broken down into three components [36]:

- Beam Component (G_b): This refers to the portion of solar radiation that comes directly from the sun and strikes the tilted surface without any scattering or reflection.
- Diffuse Component (G_d): This portion represents the scattered solar radiation that reaches the surface after being deflected by particles in the atmosphere.
- Reflected Component (G_r): This is the radiation that is reflected from the ground and subsequently received by the tilted surface.

It can be calculated using the following equation [37].

$$GSI_i = G_b + G_d + G_r \tag{1}$$

The incidence angle between the sun's rays and the surface normal can be utilized for calculating the G_b. It can be expressed as [37]:

$$G_b = \frac{G_{DH}}{cos\theta_z} cos\theta_i \tag{2}$$

Where G_{DH} direct horizontal solar irradiance, θ_z is the solar zenith angle (Eq. (3)) and θ_i is the incidence angle of the beam radiation on the tilted surface (Eq. (4)).

$$cos\theta_z = sin\phi \cdot sin\delta + cos\phi \cdot cos\delta \cdot cos\omega \tag{3}$$

$$cos\theta_i = sin\delta \cdot sin\phi \cdot cos\beta - sin\delta \cdot cos\phi \cdot sin\beta \cdot cos\alpha + cos\delta \cdot cos\phi \cdot cos\beta \cdot cos\omega + cos\delta \cdot cos\phi \cdot sin\beta \cdot cos\alpha \cdot cos\omega + cos\delta \cdot sin\beta \cdot sin\alpha \cdot sin\omega \tag{4}$$

Where δ is the solar declination angle, ϕ is the location's latitude, ω is the hour angle, β is the surface tilt angle concerning the horizontal plane and α is the surface azimuth angle.

The ω is computed using the local apparent time (LAT). Two modifications can be made to the normal time shown on a clock to accomplish this: The location's longitude and the meridian that serves as the basis for standard time disagree, which leads to the first correction. For every degree of longitude variation, the adjustment has a magnitude of 4 minutes. The Earth's orbit and rotational speed are prone to minute fluctuations, which is why the second correction is known as the equation of time (EOT). Eq. (6) is used to calculate the ω [37].

$$\omega = 15(12 - LAT) \tag{5}$$

$$LAT = standard\ tim\ (clock\ time) \pm 4(standard\ time\ longitude - longitude\ of\ location) + EOT \tag{6}$$

$$EOT = 229.18\left(0.000075 + 0.001868 \cdot cos\left(\frac{360\cdot(N-1)}{365}\right) - 0.032077 \cdot sin\left(\frac{360\cdot(N-1)}{365}\right) - 0.014615 \cdot cos2\left(\frac{360\cdot(N-1)}{365}\right) - 0.04089 \cdot sin2\left(\frac{360\cdot(N-1)}{365}\right)\right) \quad (7)$$

Where N is the day of the year.
It should be noted that the first correction for LAT applies to the eastern hemisphere with a negative sign, while the western hemisphere applies to the positive sign.

2.4 Electricity generated by the PV system

The PV system's monthly energy output can be estimated by considering key factors such as the installed system capacity, the peak sun hours at the location, and a derate factor that accounts for the combined effects of component efficiencies, system losses, and environmental conditions. The amount of electricity that a photovoltaic system is anticipated to produce can be estimated with this method. To calculate the energy output of a PV system (E_{PV}) in kilowatt-hours (kWh), utilize the formula below [38]:

$$E_{PV} = \sum_{i=1}^{n} \eta_{PV} P_{STC}\left(\frac{G}{G_{STC}}\right)\left[1 - \alpha_p(T_C - T_{STC})\right] N \Delta t_i \quad (8)$$

Where η_{PV} is the individual PV module derating factor, which accounts for wiring losses, inverter inefficiency, component failures, soiling, and aging, among other effects (η_{PV} = 0.85 here); PSTC is the nominal power of an individual PV module in terms of power output under Standard Test Conditions (STC); G is the effective, or plane-of-array irradiance, i. e. incident irradiance less self-shading losses; G_{STC} is the reference plane of-array irradiance under STC = 1 kW/m^2; α_p is the PV panel temperature coefficient of power; T_C is the operating cell temperature; T_{STC} is the STC operating cell temperature = 25°C; N is the number of installed PV modules; and Δt_i is the duration of the n time steps considered.

2.5 Electricity generated by a wind turbine

According to previous studies [39], Eq (9) can be used to express the wind turbine's total power output (E_{WT}). Furthermore, a parabolic law, as provided by [21] (Eq (10)), can be used to approximate the wind turbines' power curve.

$$E_{WT} = \sum_{i=1}^{n} P_{wt(i)}\, t \quad (9)$$

$$P_{wt(i)} = \begin{cases} P_r \frac{v_i^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} & (v_{ci} \le v_i \le v_r) \\ \frac{P_r}{v_r} & (v_r \le v_i \le v_{co}) \\ 0 & (v_i \le v_{ci} and v_i \ge v_{co}) \end{cases} \quad (10)$$

Where v_i is the vector of possible wind speeds at a given site, $P_{wt(i)}$ is the vector of the corresponding wind turbine output power in W, P_r is the rated power of the turbine in W, v_{ci} is the cut-in wind speed (m/s), $v_r$is the rated wind speed (m/s) and v_{co} is the cut-out wind speed (m/s) of the wind turbine.

2.6 Mathematical modeling of wind and solar panels

The electricity generated by the wind turbine and solar panels can be used to compute the hybrid system's total power production. Power produced (E_{Total}) by a solar-hybrid system is represented mathematically as given below.

$$E_{Total} = N_W E_{WT} + N_{PV} E_{PV} \quad (11)$$

Where N_{PV} and N_W are several solar panels, and wind turbines, respectively.

2.7 Economic viability

The economic viability of installing a PV system is assessed in this study using a variety of financial factors. These offer a comprehensive view of the project's financial performance and include the simple payback period (SPP) and the levelized cost of energy (LCOE) [40]. In the current study, the mathematical equations are used to evaluate the economic viability of the proposed hybrid system. The simple payback period (Eq (12)) provides a quick estimate of how long it will take for the initial investment to be recouped by the system's energy savings or revenue, making it a useful tool for evaluating investment risk and identifying projects with faster returns.

$$SPP = \frac{Investment\ cost}{Annual\ Saving} \quad (12)$$

Furthermore, the LCOE (Eq (13)) represents the average cost per kilowatt-hour of electricity generated during the system's lifespan and accounts for all capital, operating, and maintenance costs. This metric is crucial for assessing the PV system's cost-effectiveness in comparison to other energy sources and technologies, enabling informed decisions about long-term energy planning and investment. Collectively, these measures help stakeholders assess the short- and long-term financial sustainability of solar energy projects.

$$LCOE = \frac{C_o + \sum_1^n \frac{C_{i,t} + C_{O\&M,t}}{(1+i)^t}}{\sum_1^n \frac{E_t}{(1+i)^t}} \quad (13)$$

Where C_o is the investment cost, n is the project's economic life, $C_{i,t}$, $C_{O\&M,t}$, and E_t are the investment cost (such as replacement cost), operation and maintenance cost, and the electricity generated per year, respectively.

2.8 Carbon mitigation analysis

The proposed hybrid power plant's carbon mitigation analysis is estimated using the following methodology:

- The greatest CO_2 emissions that the hybrid power plant might reduce are given by Eq (14).

$$CO_2\ mitigation\ by\ hybrid\ system = Annual\ energy\ generation \times Emission\ factor \quad (14)$$

- The hybrid system cannot be fully regarded as an emission-free power-producing system. Therefore, it is necessary to estimate the amount of CO_2 released per kWh of power generated by the hybrid system. This uses Eq (15) to determine the emission released from the hybrid system.

$$CO_2\ emission\ from\ hybrid\ sytem = Annual\ energy\ egneration \times CO_2\ mitigation\ by\ hybrid\ system \quad (15)$$

- The net reduction in CO_2 emissions from the hybrid system facility is computed using Eq (16).

$$Net\ CO_2\ reduction = CO_2\ mitigation\ by\ hybrid\ system - CO_2\ emission\ from\ hybrid\ sytem \quad (16)$$

3. Results

3.1 Energy production variation

The present study utilizes hourly solar and wind energy data from January 1 to December 31, 2023, to estimate the renewable energy production of a 40 kW wind–26 kW solar hybrid system at the Ikas supermarket at Near East University. Due to the rapid advancement of technology, there are numerous varieties of monocrystalline solar panels available on the market, and new models are always being released. For the proposed hybrid power system, the Tiger Neo N-type 72HL4-(V) 585-watt monocrystalline solar panel was selected due to its robust power production, durable construction, and high efficiency. This panel achieves an efficiency of 22.65% by utilizing N-type TOPCon cell technology, which offers greater energy conversion and enhanced performance in high-temperature and low-light settings. Reliability and long-term power generation are supported by its low degradation rate, which is only 0.4% annually after the first year and about 1% during the second. Additional technical information regarding the solar panel may be found in Table 2.

Moreover, a 10 kW rated RX-SV2 Spiral-Type Vertical Axis Wind Turbine was employed In this investigation It was designed by Nantong R&X Energy Technology Co., Ltd.. This spiral-type Vertical Axis Wind Turbine is created for optimal performance and has a low start-up wind speed of 2 m/s. When installed at a height of 12 meters, it can operate effectively even in mild breeze. With a projected 20-year lifespan, the turbine offers a reliable choice for small-scale wind energy generation. The complete technical characteristics are shown in Table 3.

Table 2. Solar panel specification

Parameters	Value/Units
Manufacturer	Jinko solar
Model	JKM585N-72HL4
Panel weight	28 kg
Wp/panel	585W
Voltage at Maximum Power	42.52V
Current at Maximum Power	13.76A
Open-circuit voltage, Voc	51.16V
Short-circuit current, Isc	14.55A
Panel efficiency	22.65 %
Annual Degradation Rate	0.4%
Warranty	30 years

Table 3. Wind turbine specification

Parameters	Value/Units
Model	RX-SV2
Blades Height	2.0 m
Wind Wheel Diameter	1.2 m
Rated Power	10 kW
Rated Speed (m/s)	11 m/s
Start-Up Speed (m/s)	2 m/s
Survival Speed (m/s)	45 m/s
Lifetime (Years)	20

This is carried out to determine the number of electric vehicles that the recommended system can charge. Figure 2 shows the daily fluctuations in the production from the wind and solar systems for each month. It is found that wind energy varies greatly, reaching a maximum of 35,000 kWh during the winter months of January through February. On the other hand, solar energy, which typically ranges from 100 to 250 kWh per day, is more reliable but has a smaller amount. In March, the pattern is still present, with the sun making a steady contribution and the breeze showing only slight fluctuations. While solar energy steadily and considerably increases, often topping 250 kWh/day, wind output fluctuates but loses its supremacy in April and May. Moreover, during the summer months (June to August), solar energy is the most prevalent source, with daily outputs consistently exceeding 250 kWh and exhibiting minimal volatility, in contrast to wind energy, which is less dependable and usually moderate to low. Solar energy starts to slightly decline but remains stable in September and October, while wind output becomes more erratic with sporadic high peaks, particularly in October. In November and December, wind energy output increases in activity and variety, signaling a return to wind-dominated contributions, while solar energy output reaches its lowest points of the year.

Overall, solar energy is more dependable throughout the year, especially in the spring and summer, whereas wind energy is more irregular but has significant potential throughout the winter and transitional seasons. The hybrid architecture of the system ensures more consistent energy output throughout the year by utilizing the seasonal strengths of both sources. The overall daily energy output of a hybrid renewable energy system varies hourly for each month of the year, as shown in Figure 3. Since wind speeds and solar irradiance fluctuate throughout the year, the graphs provide insight into the seasonal and diurnal behavior of the system. It is found that energy output production shows clear diurnal trends, with the highest energy generation typically occurring during the day, especially between 8:00 and 16:00, which corresponds to the hours of greatest solar energy. In many months, especially in spring and early summer, the majority of the daily energy yield is contributed during these hours. March has the largest total energy output of any month, peaking at nearly 13,500 kWh between 13:00 and 14:00, indicating favorable wind activity and strong solar irradiation, and April, June, and November also have significant energy outputs, with each month reaching close to or exceeding 10,000 kWh at midday. However, October and September exhibit the lowest energy output, with maximum values of no more than 4,000–5,000 kWh, even during peak hours.

In October, the energy profile is rather flat and does not fluctuate much during the day, as shown in Figure 3. This could be a result of both decreased wind speeds along shorter daylight hours. The lower and irregular output pattern in September also points to less-than-ideal conditions for solar and wind sources during this summer-to-fall transition. Moreover, the pattern of energy generation becomes more complex during the summer months of June, July, and August. The output has a bimodal distribution in July and August, with two distinct peaks that may be observed in the early morning and late afternoon, suggesting that wind energy contributes more during off-solar hours or cloud-induced solar intermittency.

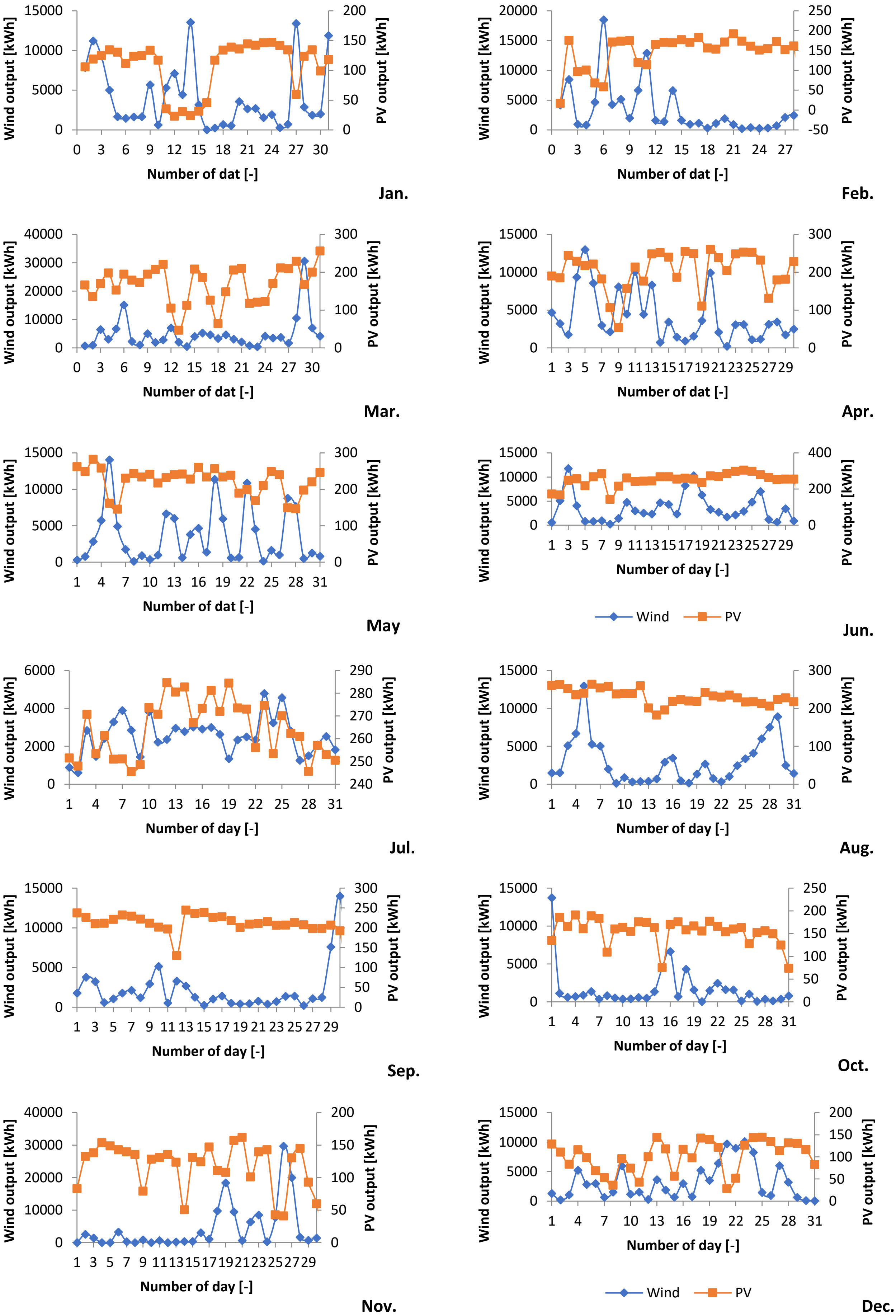

Figure 2. Daily fluctuations in the production from the wind and solar systems for each month

July is noteworthy for having two mild peaks at 6:00 and 18:00, as well as a noon decline, suggesting that wind energy becomes more prevalent during these periods due to either lower solar irradiance or PV module overheating, which reduces efficiency. In the winter months of January, February, and December, the system generates a considerable amount of energy, despite the production curve being considerably compressed. Given that the wind component compensates for less solar exposure, the hybrid system performs well even with fewer daylight hours, as evidenced by the fact that January peaks at roughly 11,000 kWh between 11:00 and 13:00, and December reaches up to 8,500 kWh. In February, the output curve is flat and peaks at roughly 7,500 kWh, indicating consistent but decreased generation. The energy generation profiles for April and May are balanced; April's energy output is constant between 8:00 and 17:00, averaging between 9,000 and 10,000 kWh during these hours, while May's high is approximately 8,500 kWh. These months provide the ideal conditions for solar energy production due to the longer daylight hours and milder temperatures that enhance PV performance. The most productive seasons in terms of total daily energy generation are spring (March) and late fall to early winter (November–January) because of a balance between the availability of solar and wind resources. Late summer and early fall witness somewhat reduced outputs, most likely due to slower wind speeds and possible decreases in PV efficiency caused by hot weather.

3.2 Results of estimating the number of EVs and chargers

In general, Nissan Leaf (battery capacity = 62 kWh) Tesla Model 3 (battery capacity = 82 kWh), Kia e-Niro (battery capacity = 64 kWh), Renault Zoe (battery capacity = 41kWh), BMW i3 (battery capacity = 42 kWh), GÜNSEL B9 (battery capacity = 53 kWh) and GÜNSEL J9 (battery capacity = 85 kWh) are the most available EVs in Northern Cyprus. In this study, a 22 kW public/commercial charger was used. Accordingly, Figure 4 shows the number of EVs, assuming one complete recharge per vehicle every session, that could potentially be fully charged by a public or commercial 22 kW charging station. According to data, the BMW i3 and Renault Zoe have the highest monthly charging capacity, with 3,500–3,700 vehicles in March. The monthly charging volume of the Tesla Model 3 is 800 to 1,800 cars, which is comparatively stable despite being lower. March and October see the highest and lowest variations for the Nissan Leaf and Kia e-Niro, respectively, indicating periodicity in supply or demand. The GÜNSEL J9 has a lower monthly total generally; however, the GÜNSEL models, especially the B9, have consistent average numbers.

It should be noted that the power used for charging is provided by a hybrid renewable energy system that combines wind turbines and photovoltaic solar panels. Since shorter charging times are required, smaller-capacity vehicles such as the Renault Zoe and BMW i3 are charged more frequently and reach monthly peaks of over 3,500 vehicles. EVs with higher batteries, such as the Tesla Model 3 and Kia e-Niro require fewer monthly recharges. Seasonal variations are present in all models, with increased charging capacity in months such as March, presumably optimum solar irradiation and wind speed conditions that maximize the hybrid setup's energy contribution. However, September and October show a decline in numbers, which could be the result of a lower supply of renewable energy. To develop and manage an effective charging infrastructure, it is critical to understand how EV characteristics, energy system performance, and seasonal energy supply interact.

Moreover, Figure 5 illustrates the number of EV chargers that can be sustained per day each month from the energy produced by a hybrid renewable energy system. The number of supported chargers and the energy availability vary significantly across days and months. It peaks in March and November, when the system may be able to handle up to 58 chargers a day, perhaps as a result of favorable wind and solar energy combinations. While August, September, and December have comparatively fewer chargers available, June, April, and February also exhibit relatively frequent peaks, suggesting lesser hybrid energy generation throughout these months. Further, the range is extremely high even within the same month, indicating the intermittent nature of renewable energy. On some days, for example, there are very few chargers (under 5), whereas on other days, it exceeds 20 or even 50 easily. This necessitates flexible energy management and storage systems to balance out charging availability.

3.3 Results of economic viability

To assess the economic feasibility, certain assumptions have been made based on literature and previous investigations regarding Northern Cyprus, considering that there are, at present, no hybrid renewable EV charging schemes in Northern Cyprus. The initial investment in hybrid solar and wind EV charging stations is USD 111,078. This includes 45 PV panels costing USD 200 (USD 9,000) and 4 wind turbines costing USD 6,000 per unit (USD 24,000), which is USD 33,000 for renewable energy equipment. The Growatt inverter costs USD 15,000 with a USD 45,000 lifespan cost. Seven public chargers are priced at USD 3,000 each, totaling USD 21,000. Other costs are 3% contingency, 8.6% installation and spares, and 0.6% feasibility and engineering charges. This is a well-thought-out breakdown of the costs that ensures all significant items and charges are captured in the project budget. For financial calculations, the discount rate of 6% has been applied to capture the time value of money, as per local economic estimates and previous research on renewable energy investments. An inflation rate of 8% was also assumed following local economic trends. Operation and maintenance (O&M) costs were considered at a standard of 1.5% of the total cost of capital per year, which is a general rate applied in global renewable energy feasibility studies.

The Simple Payback Period (SPP) of the proposed hybrid (solar + wind) electric vehicle charging station has been calculated at different selling prices (SP) of electricity to observe how pricing affects the payback of the initial investment. The results demonstrate a clear trend: the more expensive the selling price per kilowatt-hour, the shorter the payback period. As shown in Figure 6, with a reduced selling price of USD 0.10/kWh, the payback period turns out to be very long, around 10.35 years, which may not attract investors. With an increased price of USD 0.31/kWh, corresponding to the current local grid electricity price, the payback period reduces to around 3.34 years, and the project turns out to be much more financially attractive. When the price is set at a premium rate of USD 0.428/kWh, the payback period shortens even more to around 2.42 years. The premium rate not only accelerates the return on investment more quickly but also recognizes the value added of clean, renewable energy and growing consumer demand for green EV charging options.

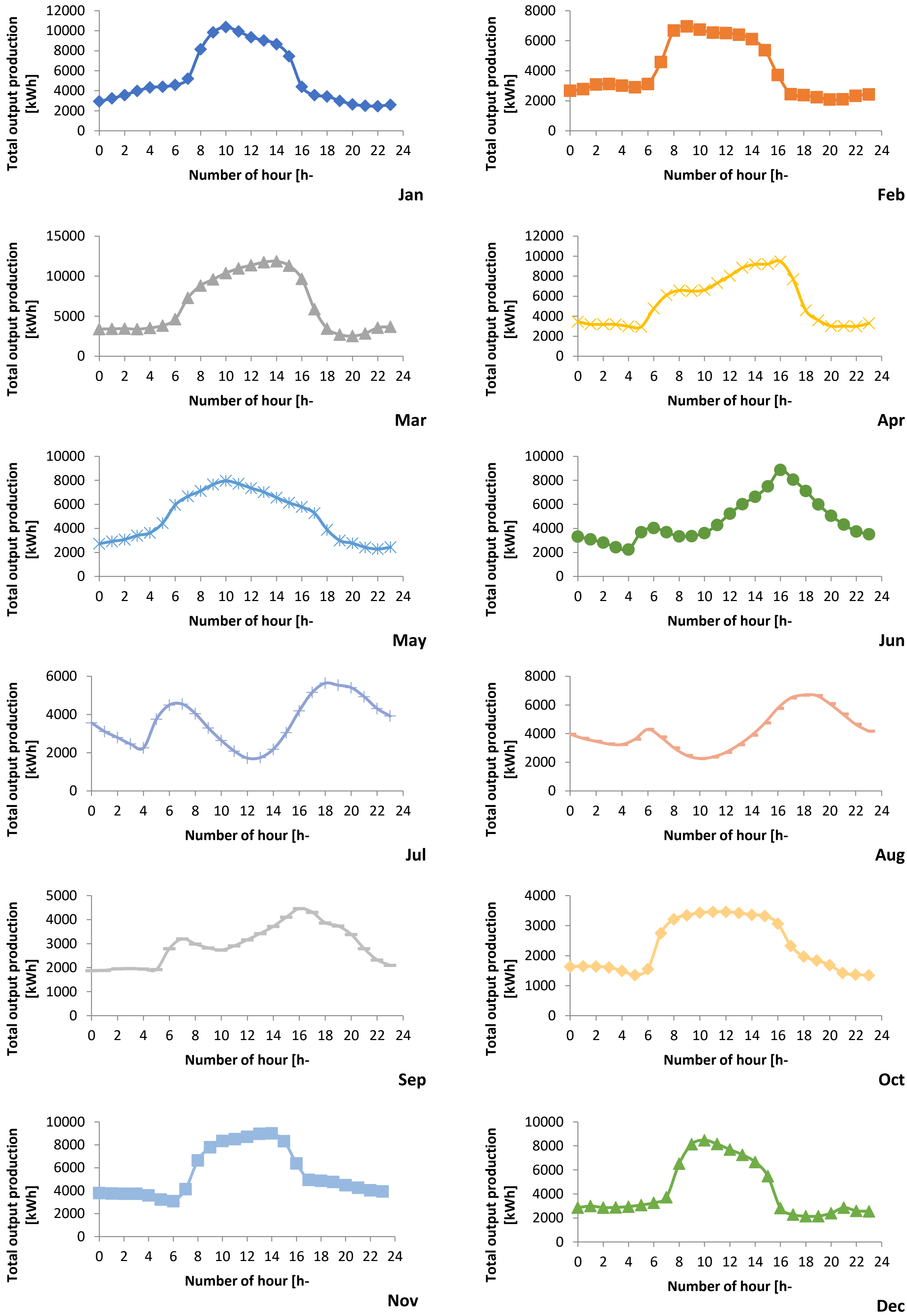

Figure 3. Hourly total energy output production from the hybrid system for each month

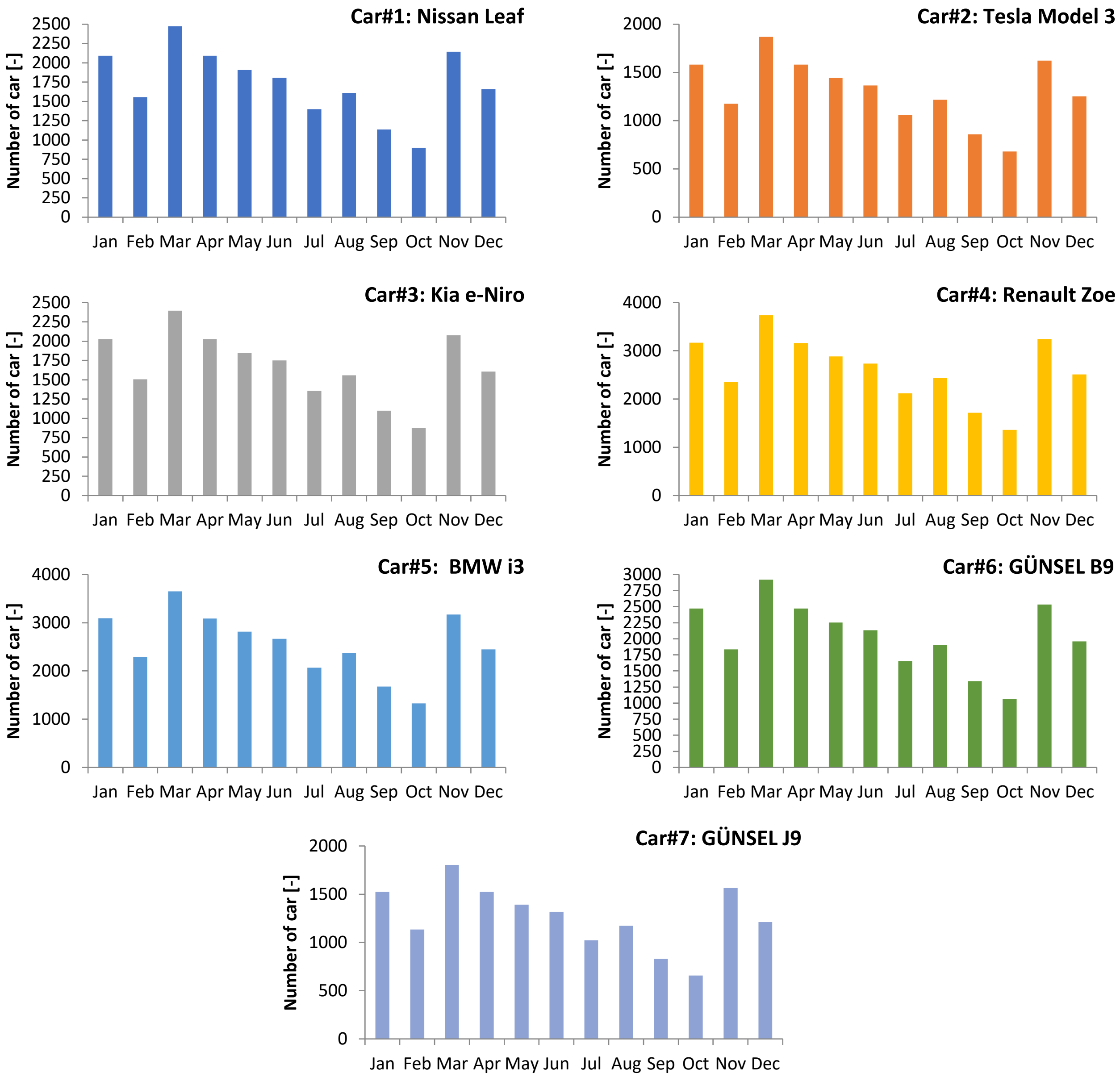

Figure 4. Estimated number of cars using public or commercial 22 kW charging station

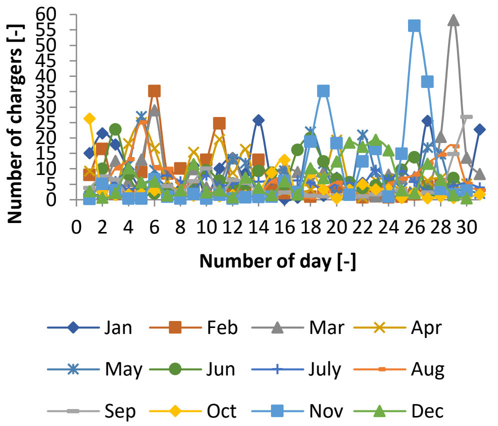

Figure 5. The estimated number of EV chargers that can be sustained per day, each month

It is such a pricing mechanism that supports quicker capital recovery, enhances profitability, and stimulates the adoption of environmentally friendly transportation. However, the proposed solar and wind power-enabled hybrid charging station can produce an average estimated 107,327.61 kWh of clean electricity annually. Because all the energy resources utilized in the system are renewable, the system has virtually no operational carbon dioxide (CO_2) emissions. In a calculation involving the overall life cycle from manufacturing to installation, maintenance, and decommissioning, an estimated emission intensity of approximately 30 grams of CO_2 per kWh is expected, which, annually, amounts to a total of around 3,219.83 kg of CO_2. To put this into perspective, if the same amount of electricity is produced by the power grid in Northern Cyprus, which is highly dependent on fossil fuels such as diesel and heavy fuel oil, the emissions would amount to 83,716.53 kg of CO_2 per year based on an average emission factor of 780 grams of

CO_2 per kWh. This translates to the estimated hybrid system achieving an average savings of approximately 80,496.70 kg of CO_2 equivalent to a 96% decrease in emissions from usual grid electricity.

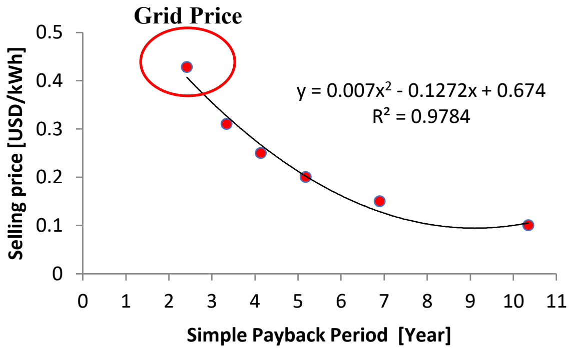

Figure 6. SPP vs. SP

Moreover, when electric cars are charged using the electricity generated by the suggested system, the resulting emissions equal 2–6 g of CO_2 per kilometer. On the other hand, grid charging contains around 156 grams of CO_2 per kilometer, while conventional petrol and diesel engines release around 185g and 160g of CO_2 per kilometer, respectively. All such comparisons demonstrate that the proposed system significantly reduces greenhouse gases and is open to sustainability and climate mitigation strategies.

3.4 Limitations and future work

The viability of a hybrid solar-wind power system for EV charging at Ikas Supermarket in Lefkoşa, Northern Cyprus, is examined in this study. Although the outcome is encouraging and suggests that locally accessible renewable energy could be used to sustainably charge EVs, it is important to identify some limitations to understand the results and influence future research. The analysis was performed using wind and solar data from the NASA POWER database. Due to a lack of on-site measurements or validation of real-time data, the results may not be accurate, which are influenced by climate conditions. Besides, the system's design is based on general consumption rate assumptions and assumed EV charging load rather than measured actual load profiles and traffic patterns for the supermarket. This adds uncertainty to economic calculations and energy sizing. Additionally, the existing model does not fully incorporate some technological factors due to scope limits, such as the long-term degradation of PV panels, the lower efficiency of windmills at low wind speeds, the integration of battery storage, and dynamic control of systems.

For accurate system performance analysis and financial modeling, these are necessary. In order to enhance subsequent research, it is suggested that energy consumption, solar irradiance, and wind speed be measured on-site, that real-time system monitoring be established, and that a sensitivity analysis of important technical and financial aspects be conducted. In Northern Cyprus and other comparable settings, such renewable-based EV charging systems will also become more dependable and scalable with the addition of battery storage systems, load control techniques, and realistic user behavior.

3.5 Conclusions

This study provides an in-depth examination of the energy potential, charging capacity, and environmental and economic sustainability of a hybrid solar and wind-powered electric vehicle charging station designed for Northern Cyprus. Based on the results, solar energy provides consistent daily output, especially in the spring and summer, while wind energy makes a substantial contribution in the winter and transitional months. These seasonal fluctuations are expertly complemented by the hybrid system architecture, which provides a steady energy output all year round. With a peak energy generation of 13,500 kWh in March and the ability to support up to 58 chargers per day, the system shows a strong capacity to meet local EV charging needs. At a selling price of $0.31/kWh and a payback period of 3.34 years, the project becomes economically viable. Once again demonstrating the system's sustainability, it offers a 96% reduction in CO_2 emissions when compared to grid-based electricity. The system's viability and usability are still supported by its monthly capacity to charge thousands of EVs, including regional models such as the GÜNSEL B9. For countries that are importing oil, EVs would have saved the money spent on importing fossil fuel for cars that run by fuel or vehicles. Many foreign currencies have been used in importing such forms of fuel, which also helps to reduce the trade deficit. Besides financial benefits, since electricity generated using solar energy can be used to charge EVs, it can go a long way in improving our environment by reducing CO_2 emissions. The government can provide simple incentives such as a lower rate of taxation for the use of electric vehicles compared to fuel-based vehicles. In addition, a cut in the import duty of the EVs and an increase in the import duty of the fuel cars can be in their favor regarding adaptability. The authority must invest in electric vehicle technologies research and development at the local level and build electric vehicle charging stations across the nation. The feasibility study shows that wind-solar charging can be profitable for charging various available types of EVs, and thus, the research findings could have great implications for countries with imported fuel at a high price. If it had been particularly constructed to use solar power in recharging EVs, and not batteries and the plant price had been reduced by almost half of the total amount, then the usefulness of this research could be more relevant. The research brought out a new dimension to the utilization of electric vehicles powered by only renewable sources of energy, a new contribution to what already exists in the literature. The findings of the study are technologically feasible, economically feasible, and environmentally friendly and therefore merit being employed by policymakers in any country.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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