

Research Article

Integration of Electric Charging Stations into Sustainable and Renewable Energy: A Case Study

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ARTICLE INFO

Received: Oct.,20.2025

Revised: Feb.,02.2026

Accepted: Feb.,08.2026

Keywords:

Electric Vehicle Charging Station
Renewable Energy Integration
Hybrid Energy System
Sustainable Transportation

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ISSN: 2536-5010 | e-ISSN: 2536-5134

DOI: <https://doi.org/10.36222/ejt.1807003>

ABSTRACT

This study evaluates the potential for sustainably operating the Electric Vehicle (EV) charging infrastructure in Bitlis Province through a wind-solar hybrid generation system complemented by an 8 MWh Battery Energy Storage System (BESS), using a representative charging site as a detailed case study. Following the development of a spatial and technical inventory of EV charging stations across the province, a station strategically located on an intercity transit corridor was selected for in-depth analysis. To this end, the demand profile was modeled on a monthly basis by accounting for the national EV penetration rate, seasonal charging frequency, and alternative charging scenarios. On the supply side, the seasonal variability of wind and solar resources was simulated at high temporal resolution using local meteorological data. The analyses indicate that single-source solutions may conflict with the objective of service continuity under the conditions prevailing in Bitlis, potentially leading to significant unmet demand during resource-scarce periods. By contrast, a hybrid wind-solar configuration, when coupled with appropriately sized storage, can render the charging infrastructure technically and operationally sustainable, achieving full year-round service continuity. In this context, a configuration comprising 10 kW of wind capacity and 5 kW of solar is proposed. Under this configuration, the lowest monthly generation is 1,315.6 kWh in November, while the highest is 7,027 kWh in March. The maximum battery storage requirement of approximately 7,134 kWh was identified, leading to the recommendation of an 8 MWh BESS to ensure uninterrupted year-round EV charging service. The system meets an average monthly demand of approximately 2,500 kWh, with surplus energy stored during high production months and deficits covered during low production periods. The cumulative energy balance indicates a surplus of 788 kWh by the end of the year, which can be utilized for emergencies or other operational needs. The study provides a transferable planning framework for regions with similar infrastructural and meteorological characteristics, demonstrating the quantitative impact of local resource integration on EV charging infrastructure resilience.

1. INTRODUCTION

Global climate change, the depletion of fossil fuel reserves, and concerns over energy supply security are driving a sustained increase in interest in Renewable Energy Sources (RES) worldwide. In this context, RES such as wind and solar have garnered growing attention due to their environmentally friendly and sustainable characteristics. Moreover, fossil fuels are responsible for carbon emissions and irreversible environmental impacts, including global warming [1]–[3]. With the increasing adoption of Electric Vehicles (EVs), the transport sector has become a pivotal domain for reducing carbon emissions. Consequently, the integration of EV charging stations with RES is emerging as a fundamental component of sustainable and renewable mobility, as well as of smart energy management systems. Among RES, solar and wind energy hold particular prominence in this regard [4]–[8].

Integrating RES with EV charging infrastructure offers significant environmental and economic benefits. These include peak demand reduction, energy optimization during off-peak periods, lower operating costs, voltage and frequency regulation, vehicle-to-grid (V2G) energy transfer, and enhanced grid flexibility. EVs also represent a promising solution for facilitating this transition in the transport sector by delivering lower emissions and improved energy efficiency [4], [9], [10]. The transport sector accounts for approximately 25% of global final energy consumption, with road transport responsible for three-quarters of its carbon emissions. Addressing this critical challenge renders the adoption of RES indispensable [7], [8].

To underscore the contemporary significance of EVs: the ultimate efficiency of internal combustion engines is approximately 14%, whereas charging EVs from conventional energy sources achieves about 52%; when RES are used, this

figure rises to around 70% [4]. Consequently, charging stations can evolve from being mere electricity consumers into active energy nodes capable of supplying power back to the grid when needed. However, the existing power system infrastructure is not designed to accommodate the heightened loads associated with periods of intensive charging demand. Each additional high-power charging station necessitates new capacity investments across generation, transmission, and distribution layers. This underscores the necessity of supporting EV infrastructure with localized renewable energy systems. Within this framework, Figure 1 summarizes the study's general methodological approach.

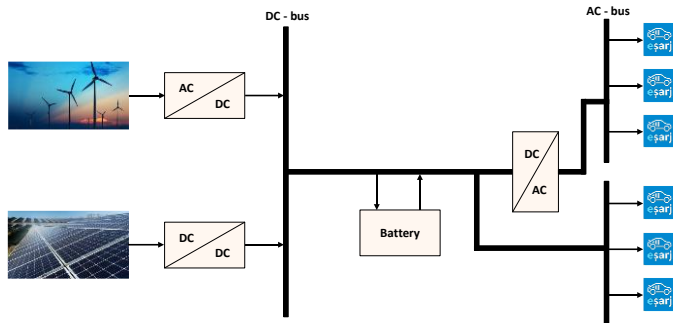


Figure 1. The study's general methodological framework

In this study, the existing EV charging infrastructure in Türkiye is assessed through the case of Bitlis Province, and the feasibility of supplying charging stations with renewable energy is analyzed using wind-solar hybrid systems. By compiling the location, capacity, resource potential, and demand parameters of charging stations across the province, an appropriate hybrid system sizing is proposed. The long-term objective of the study is to develop a regional model for sustainable charging infrastructure aligned with the goal of carbon-neutral cities. The technical modeling and simulation of renewable energy generation and storage systems were conducted using MATLAB, employing customized scripts that integrate high-resolution, site-specific meteorological

data from the Global Wind Atlas and Global Solar Atlas. This approach enabled precise calculation of wind turbine power output, photovoltaic module performance, and battery energy balance under realistic operational conditions, thereby ensuring robust and replicable results.

1. 1. Literature Summary

As in many sectors of industry, energy transition technologies in road transportation are rapidly evolving in line with sustainability targets. Recent studies demonstrate that addressing EV charging infrastructure in an integrated manner with RES and energy storage systems yields substantial improvements in both emissions and operating costs. In this context, hybrid architectures are attracting increasing attention in the literature due to their high specific power, fast dynamic response, and low emission profiles. However, load profiles in road transportation are multi-stage, repetitive, and variable, which both heightens the need for comprehensive experimental validation and complicates early-stage design processes. Consequently, flexible models capable of producing fast, reliable, scenario-based outcomes at the preliminary design stage are of critical importance.

Another study presents a technical, economic, and environmental assessment of EV charging stations powered by hybrid intermittent generation systems across three cities in Ethiopia. Employing three different battery chemistries, the proposed hybrid systems are subsequently compared in terms of system sizing, economics, technical performance, and environmental sustainability. The findings indicate that configurations combining photovoltaics, diesel generators, and ZnBr battery systems are viable [3]. Within this scope, one study conducted in Kentucky investigates the integration of photovoltaic and Wind Power Plant (WPP) augmented by green hydrogen production based on observed EV load profiles into EV charging stations [11].

TABLE I
LITERATURE SUMMARY

Reference	Type of RES	Location	Key Findings
[11]	Wind, solar, BESS, hydrogen	USA	The integration of photovoltaic (PV)/wind-battery-hydrogen systems based on EV load profiles is techno-economically feasible. Moreover, the potential for hydrogen utilization in light- and heavy-duty vehicles through 2040 is projected to be promising for low-carbon transportation.
[14]	Wind, solar, diesel generator, BESS	Denmark	The hybrid charging station was evaluated from technical and economic perspectives and subsequently sized. The resulting configuration recommends 30 kW of PV, 12 kW of wind, a 10 kW diesel generator, and battery capacities ranging from 98 to 185 kWh across the evaluated regions.
[3]	Wind, solar, diesel generator, BESS	Ethiopia	An average daily EV load of 3,216 kWh was proposed, and among the evaluated battery technologies, ZnBr was found to offer longer service life and to reduce costs in charging station applications due to its favorable characteristics.
[10]	Wind, solar, biogas, BESS		It is shown that enabling PV based EV charging stations under continuity and power quality constraints necessitates the incorporation of energy storage systems and hybrid renewable integration. The analysis further concludes that factors such as site/space requirements, battery aging, and life-cycle emissions remain decisive in techno-economic design.
[15]	Solar, BESS, on-grid	India	Using HOMER optimization, a grid-connected, battery-buffered EVCS comprising 3 kW of PV was deployed on a campus. The system achieved an annual PV yield of approximately 6,474 kWh and delivered reliable power at minimum annual system cost for a typical daily charging demand of 15 kWh over an 8-hour period.
[16]	Wind, solar, on-grid, BESS	India	By optimizing the sizing of EV charging stations in a grid/PV/wind hybrid configuration using the Modified Salp Swarm Algorithm, the study minimizes total net present cost and levelized cost of energy while maintaining the probability of power supply failure at an acceptable level.
This Study	Wind, solar, BESS	Türkiye, Bitlis	Following the assessment of RES potential at the charging station locations, EV load profiles were analyzed on a monthly basis by accounting for seasonal variability in charging behavior and alternative charging scenarios. Based on these analyses, a hybrid configuration comprising 10 kW of wind capacity and 5 kW of PV is proposed. In addition, to ensure year-round service continuity, a BESS with a capacity of 8 MWh is envisaged.

In a separate work utilizing HOMER software, the hybrid operating modes of RES for the integration of EVs with charging stations are examined [12]. Similarly, integration studies using MATLAB/Simulink have been conducted for EV charging stations [13]. Another contribution analyzes the design and performance of a hybrid energy-based EV charging station in Denmark. The mathematical modeling of the proposed EV system operating with a combination of photovoltaics, wind turbines, diesel generators, and storage is examined, and performance is evaluated for four locations in Denmark using HOMER [14]. Furthermore, to facilitate comprehension of the reviewed literature, Table 1 systematically categorizes references on RES integrated EV charging stations according to their main themes. In addition to hybrid system studies, recent work has focused on the detailed performance assessment of grid-connected PV plants under real operating conditions. Analyze the performance ratio of a 250 kWp solar power plant using IEC 61724 indicators and PVsyst-based simulations, highlighting the gap between simulated and measured yields and the importance of site-specific performance evaluation for reliable PV integration [17].

In summary, the existing literature on RES integrated EV charging infrastructures predominantly focuses on techno-economic optimization of generic system configurations, often using simulation tools such as HOMER or MATLAB/Simulink under assumed or idealized load profiles. Most studies emphasize sizing and cost minimization for PV–wind-diesel or grid-connected hybrid systems, frequently at the level of conceptual station designs or representative scenarios rather than using detailed, location specific charging data. Moreover, while several works consider different battery chemistries or hydrogen production, relatively fewer studies explicitly integrate real station-level spatial distributions, locally observed wind and solar resource patterns, and seasonally varying EV charging behavior into a unified planning framework. Against this background, the present study distinguishes itself by (i) employing a province-wide inventory of existing charging stations in Bitlis, (ii) constructing a monthly EV demand model that accounts for seasonal variation in charging frequency and battery efficiency, and (iii) evaluating a wind solar BESS configuration under the actual meteorological conditions of a specific transit corridor. Thus, the contribution of this work lies less in proposing a new optimization algorithm and more in providing a data-driven, regionally grounded case study that can be transferred to similar provincial contexts.

The final assessment of the tables and reviewed literature indicates that the techno-economic integration of RES in EV charging stations is being examined with increasing depth. However, the selection of an optimal configuration requires case-specific evaluation due to local RES potentials, site and grid constraints, power quality requirements, and the temporal variability of charging/load profiles. Consequently, scenario-based and flexible modeling approaches that represent diverse demand and resource conditions are of critical importance.

1. 2. Motivation

The increasing number of EVs on the road is driving higher electricity demand. In regions with intensive EV use, sudden surges in charging demand can induce voltage fluctuations, line overloading, and localized power quality issues on existing grids. As current power systems were designed for

traditional load profiles, they are inadequate for meeting today's mobility centered electricity demand and an inadequacy that becomes more pronounced with the proliferation of high-power fast-charging stations. The literature further indicates that the energy consumption of charging stations varies with numerous parameters, including regional climatic conditions, vehicle density, and user behavior [8]. Consequently, renewable energy-based charging systems optimized to local meteorological and topographical characteristics are required for each region.

In the context of Türkiye, fast-charging infrastructure is still in a developmental phase, and a substantial portion of energy supply remains fossil fuel based. Rising EV penetration entails higher power demand, which risks increasing the carbon intensity of energy supply. Direct integration of RES therefore presents a critical opportunity from both sustainability and energy independence perspectives.

The primary motivation of this study is to demonstrate the technical feasibility of supporting EV charging infrastructure with RES using the case of Bitlis Province. The aim is to balance increasing energy demand with local RES potential rather than relying on fossil sources and to reduce the burden on the grid. In the long term, this approach is expected to both lower the carbon footprint of the charging infrastructure and contribute to national energy supply security.

Recent advancements in hybrid renewable energy system optimization for electric vehicle charging stations have focused on diverse aspects, including multi-objective sizing and techno economic assessments for various configurations, the integration of green hydrogen production from excess renewable energy, and the application of advanced metaheuristic algorithms for economic energy management in microgrids [11], [18], [19].

1. 3. Innovations and Contributions

This study constitutes a pioneering regional application on the integration of RES with Türkiye's nascent EV charging infrastructure. Its principal novelty lies in evaluating hybrid system design under local meteorological conditions using real field data from Bitlis Province. Whereas much of the literature focuses on generic system models or theoretical optimizations, this work uniquely:

- Identifies local energy potential based on station-level datasets.
- Constructs a per-vehicle energy consumption profile that accounts for seasonal demand variability and directly integrates this profile into system design.
- Develops wind–solar hybrid generation scenarios and demonstrates that the share of renewables in charging infrastructure can be maximized.
- Assesses energy storage integration to reduce grid dependency and enhance supply security.

Therefore, the proposed framework targets not only generation capacity but also sustainable energy management at the charging-station level. In this study, rather than providing a detailed techno-economic evaluation, the focus is on demonstrating the technical feasibility of the proposed hybrid wind–PV–BESS configuration for EV charging stations. At the same time, the results indicate that this configuration has the potential to reduce dependence on fossil-based electricity and to contribute to the reduction of carbon emissions, thereby supporting the development of a greener and more sustainable transportation and energy system.

2. MATERIALS AND METHODS

2.1. Limitations of the study

This study presents a case analysis of integrating wind–solar hybrid resources with the EV charging infrastructure in Bitlis Province, Türkiye. Its scope is defined within specific methodological assumptions and limitations, as outlined below:

Geographical scope: The analysis is confined to the administrative boundaries of Bitlis Province. Charging station locations within the province and their associated wind and solar resource data are employed.

Demand model: Charging demand is modeled based on typical user behavior and climatic conditions reported in the literature. While modern EVs commonly offer ranges of at least 300 km, the average daily driving distance is approximately 30 km in the United Kingdom and around 60 km in the United States. It is therefore assumed that vehicles are typically charged once per week or less frequently. On this basis, four charging sessions per vehicle per month are considered for summer, and five per month for winter, reflecting a 25% increase due to reduced battery efficiency and heating loads. This approach captures the impact of seasonality on energy consumption.

Energy consumption profile: Per-vehicle energy requirement is evaluated under two charging window scenarios optimistic and pessimistic. The pessimistic case, defined as charging from 10% to 90% state of charge, is adopted as the reference for system design.

Grid interaction: Surplus electricity is stored in batteries for later use. In the event of additional surplus, it is assumed to be exported to the electricity supplier at \$0.02/kWh; conversely, imports are assumed at a tariff of \$0.07/kWh when needed [8]. These unit prices are adopted as representative values following and typical wholesale/retail tariffs in Türkiye; a detailed tariff and regulation based cost optimization is beyond the scope of this study.

Vehicle count: Prior studies indicate that the number of EVs and plug-in hybrids sold in China scales proportionally with population relative to other regions worldwide [7]. Therefore, for the case study, the number of EVs in the province is estimated based on the ratio of local total vehicles to the national total, using official data sources.

In accordance with the exploratory and planning-oriented scope of this work, the analysis is conducted on a monthly energy basis. This temporal resolution is sufficient to capture the dominant seasonal trends in wind and solar resources as well as in EV charging frequency at the provincial scale. A full hourly co-simulation of generation, EV load, and BESS operation would require detailed traffic-flow and user-behaviour data, together with an explicit operational control model for the storage system, which are beyond the data availability and objectives of the present case study. Consequently, the proposed framework should be regarded as a first-step regional screening tool, while the development of an hourly, operation-level model for specific sites is identified as an important direction for future research. This study employs a monthly energy balance approach, which is appropriate for preliminary, regional-scale assessment and planning. However, it is acknowledged that higher temporal resolution analyses, such as hourly simulations, are necessary to capture transient phenomena including rapid fluctuations in electric vehicle charging demand and the dynamic interactions

with BESS. The development of such high resolution co-simulation models requires detailed datasets on traffic flow, user charging behavior, and storage control strategies, which are currently beyond the scope and data availability of this work. Future research will focus on addressing these limitations by integrating comprehensive operational data and implementing validated hourly simulation frameworks to enhance the accuracy and applicability of the proposed system.

2.2. Data set

In this study, a comprehensive dataset was employed to evaluate the current state of EV charging infrastructure in Bitlis Province and its potential for renewable energy integration. The dataset comprises 23 charging stations distributed across the province, as presented in Table 2. The station shaded in grey in Table 2 (ID: S/8411) is used as the reference case-study charging station in this work.

Meteorological data such as wind speeds and solar irradiance used for the renewable energy production estimates were obtained from validated, high-resolution real-world datasets and were employed to derive the energy potential presented in Table 2 for the Bitlis region [20], [21]. A generic 4.0 MW – IEC Class 1 wind turbine model was used for the wind energy production estimates. This detailed turbine information, together with the solar panel performance assumptions, is inherently integrated into the methodologies of these global datasets.

TABLE II
ELECTRIC VEHICLE CHARGING STATION DATA

Station ID	AC/DC	Power (kW)	Lat.	Lon.	Wind Speed (m/s)	DNI (kWh/m ²)
S/2734	AC	2x22	38.503	42.220	4.49	1988.4
S/4989	AC	2x22	38.448	42.147	7.39	1896.9
S/5644	DC	2x180	38.757	42.520	3.77	2073.8
S/6462	DC	2x180	38.506	42.226	5.17	1989.7
S/8000	DC	2x180	38.465	42.136	8.24	1894.3
S/9080	DC	2x60	38.386	42.103	5.98	1850.9
S/10944	AC	4x11	38.521	42.260	4.3	1991.1
S/11211	AC	2x22	38.386	42.103	5.98	1850.9
S/8411	DC	2x120	38.458	42.540	5.84	1893.3
S/8451	DC	2x120	38.443	42.146	7.15	1948
S/12258	DC	2x120	38.609	42.395	3.86	1994
S/14532	DC	2x150	38.482	42.298	4.52	1847.1
S/5858	DC	2x180	38.406	42.106	6.69	1920.3
S/5450	DC	2x120	38.494	42.285	4.93	1940.1
S/5453	DC	2x120	38.511	42.277	4.93	1940.2
S/5502	DC	2x120	38.298	42.000	7.65	1794.1
S/5503	DC	2x120	38.485	42.175	5.44	1970
S/5446	DC	2x120	38.793	42.710	4.71	1997
S/5454	DC	2x120	38.579	42.01	2.21	1934
S/6471	AC	1x11	38.521	42.267	4.4	1987.8
S/16113	AC	1x22	38.580	42.021	2.22	1939.1
S/17786	DC	2x180	38.503	42.220	4.49	1988.4
S/10347	AC	1x11	38.521	42.267	4.28	1987.8

In this study, all energy production and storage capacity calculations were performed using standard deterministic engineering equations for wind turbines, PV modules, and battery energy balance, based on the obtained meteorological inputs. MATLAB was used exclusively for these calculations and for the visualization of the results.

The geographical distribution of these charging stations across Bitlis Province is depicted in Figure 2. Red markers denote existing EV charging stations, while the black marker indicates the reference location used for the case study in this work.

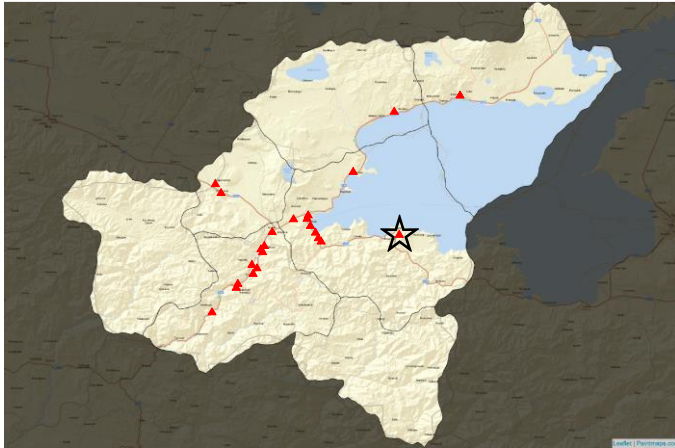


Figure 2. Geographic distribution of EV charging stations

The location selected for the case study was determined based on its strategic significance. Situated along major intercity transit routes in Bitlis and hosted within a service area, the station represents an ideal example given both the high potential for vehicle traffic and the critical need for charging on long-distance journeys. Moreover, its placement within an integrated facility such as a rest area offers suitable space and infrastructural potential for the installation and operation of renewable energy systems. This selection enables a more realistic assessment of the study's findings in terms of their impacts on and applicability to regional transportation networks.

2. 3. Energy consumption profile

The energy consumption/load profile of EVs is a critical parameter for charging infrastructure planning and renewable energy integration studies. In this work, the estimation of energy demand is based on the projected number of EVs in Bitlis Province, charging frequency, battery state-of-charge levels, and seasonal variability. Based on this approach, the number of EVs in Bitlis is estimated using the national EV penetration rate for Türkiye. Based on this approach, the EV count in Bitlis is calculated using Equation 1.

$$C_{EA} = C_{city} \times \frac{C_{totalEA}}{C_{total}} \quad (1)$$

Where C_{EA} denotes the number of EVs in Bitlis, C_{city} the total number of vehicles in Bitlis, $C_{totalEA}$ the total number of EVs nationwide, and C_{total} the total number of vehicles nationwide. Accordingly, there are 16,580,427 vehicles in Türkiye, of which 229,397 are registered as EVs [22]. In light of these figures, given that the total number of vehicles in Bitlis is 28,477 and the national EV share is 1.383%, it is estimated that approximately 394 EVs are present in Bitlis. This approach, being based directly on vehicle counts rather than indirect indicators such as population, yields more realistic and actionable results for energy consumption analyses. In constructing the energy consumption profile, it is assumed that each EV charges an average of four times per month. The resulting monthly energy requirement per socket is then calculated using Equation 2. In this formulation, the provincial EV fleet (approximately 394 vehicles) is used solely to construct an aggregate demand level, which is

subsequently normalized on a per-socket basis. This procedure does not assume that all vehicles are physically served by a single charging station. No explicit traffic-flow or corridor-usage measurements are employed; instead, the demand model relies on vehicle-count ratios combined with literature-based assumptions regarding charging frequency and per-session energy consumption.

$$E = E_{EA} \times \frac{C_{EA} \times N_c}{N_s} \quad (2)$$

Where E , denotes the monthly energy per socket (kWh), E_{EA} , the per-vehicle energy demand, N_c , the number of charging events per EV per month (set to 4 for summer and 5 for winter), and N_s the number of sockets at the charging station. Seasonal effects also play an important role in the energy consumption profile. In particular, due to reduced battery efficiency and increased cabin heating loads in winter, EV energy consumption rises by approximately 25% [23]. In addition, this study adopts a per-vehicle battery capacity of 90 kWh [24]. Ahoca choice informed by the current market composition and the representativeness needed for charging infrastructure planning. Accordingly, accounting for seasonal variability and vehicle state-of-charge considerations, the monthly energy per socket is reported in Table 3.

TABLE III
EV ENERGY REQUIREMENTS BY CHARGING RANGE

Scenario	Optimistic	Pessimistic
Charging window	%10-%80	%10-%90
Unit energy req. (kWh)	63	72
Total energy req. (summer-kWh)	2206.4	2521.6
Total energy req. (winter-kWh)	2758	3152

Based on the values presented in Table 2, demand-side analyses were conducted under two distinct assumption sets: optimistic and pessimistic. Furthermore, given the intermittency on the renewable generation side and the service quality requirements of the charging infrastructure, minimizing the risk of “unserved demand” is essential in system sizing. Accordingly, the pessimistic scenario is adopted as the design criterion for determining WPP–PV generation capacity and battery storage sizing. This approach aims to ensure that charging demand is met even under the least favorable conditions while constraining grid dependency and peak power draws.

3. RENEWABLE ENERGY POTENTIAL

3. 1. Wind Power Plant

Wind speeds increase with elevation above the Earth's surface and decrease near the ground due to frictional effects. The wind speed at one height can be estimated from measurements at another height. The most commonly used formulation for this purpose is the Hellmann equation, given in Equation 3 [25]. Wind speed measurements are typically conducted at a height of 10 m, as specified by the World Meteorological Organization. Rotor blades play a direct role in converting wind energy into mechanical energy. The difference in kinetic energy between the air impinging on and departing from the blades corresponds to the portion of wind energy converted into kinetic energy.

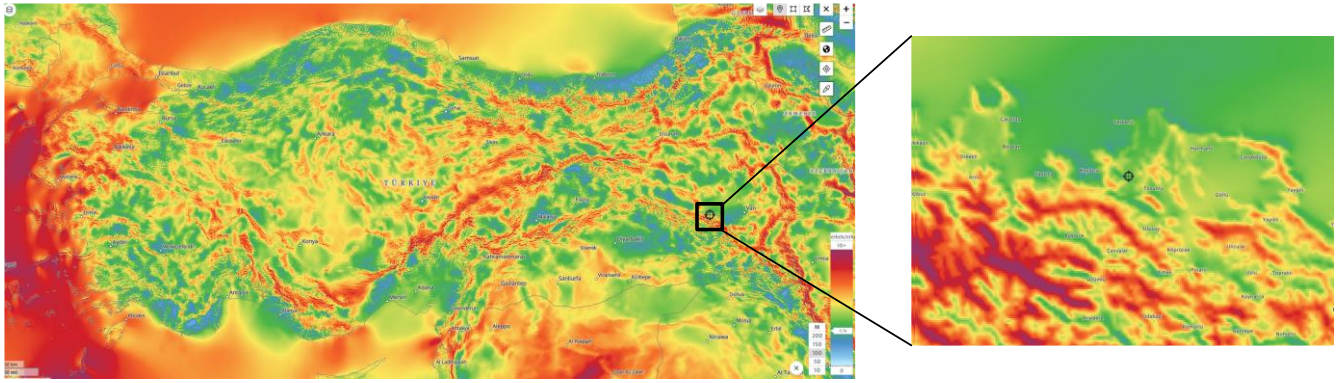


Figure 3. Wind speed map

The calculation of this power relies on kinetic energy equations. The extractable energy from a wind turbine is presented in Equation 4.

$$\frac{V}{V_0} = \left(\frac{H}{H_0} \right)^\alpha \quad (3)$$

$$E_e = \frac{\rho A}{2} v^3 t \quad (4)$$

Where ρ denotes air density (kg/m^3), A the rotor swept area of the wind turbine (m^2), v the wind speed at hub height (m/s), and t time (s). The wind speed map for the selected location is provided in Figure 3.

In calculations for the case study, monthly wind speed data are crucial, particularly when referencing the energy load profile. The monthly wind speed variation graph for the selected location is presented in Figure 4.

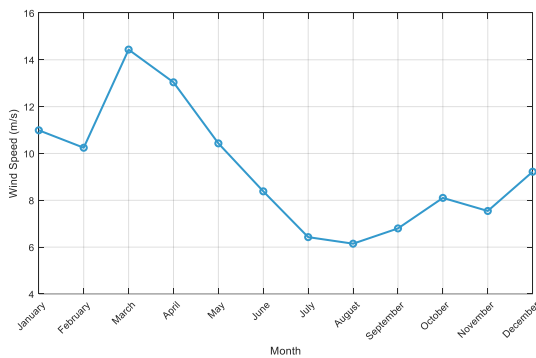


Figure 4. Monthly mean wind speed profile

At the selected location, wind speeds are markedly lower in the summer months compared to other seasons. This seasonal decline indicates that wind power alone may be insufficient to meet charging demand, particularly during the summer period.

3. 2. Solar Power Plant

Solar energy the primary source for many renewable energy Technologies is the radiant energy produced by fusion processes in the Sun's core. The energy output of a PV module depends not only on its intrinsic design but also on external factors. Solar irradiance, cell temperature, and shading are among the principal determinants of PV module efficiency and must be considered during system design. The annual energy yield from a PV module can be estimated using Equation 5.

$$E_e = A_{tp} \cdot A_v \cdot \eta_f \cdot P_R \cdot GHI \quad (5)$$

Where E_e denotes the annual electrical output of the PV module (kWh/year), A_{tp} the total PV module area (m^2), A_v the module availability, η_f the module efficiency, P_R the performance ratio accounting for losses (e.g., temperature, shading, wiring); and GHI the annual global horizontal irradiance (kWh/m^2). The GHI map for the selected location is provided in Figure 5. In addition the monthly Direct Normal Irradiance (DNI) variation graph for the selected location is presented in Figure 6.

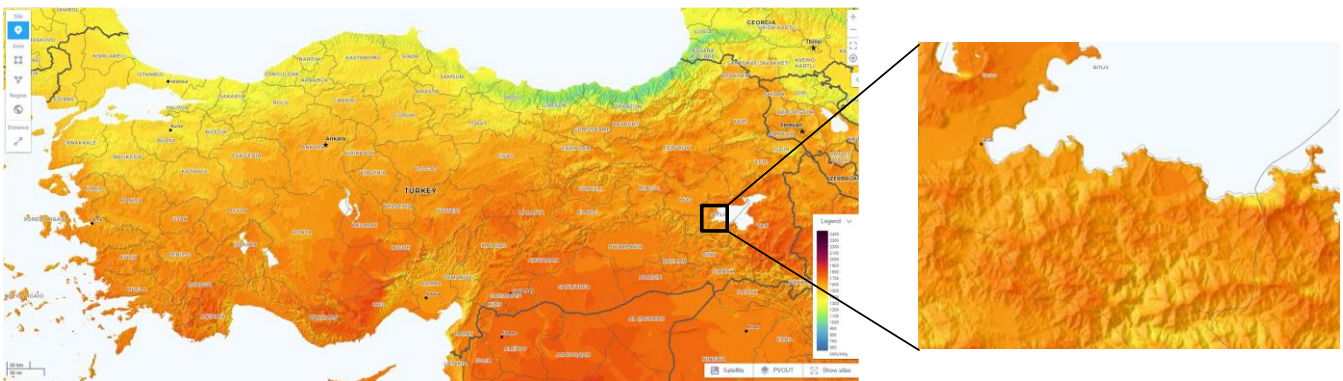


Figure 5. Map of Global Horizontal Irradiance (GHI)

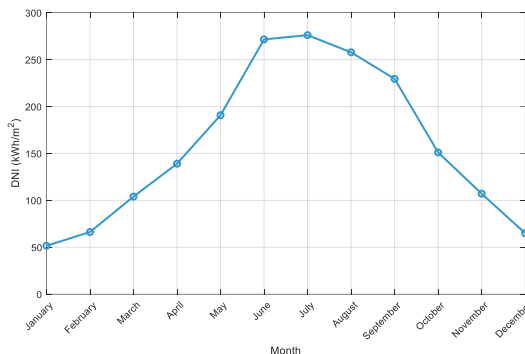


Figure 6. Monthly Mean DNI Profile

Analogous to wind variation but in the opposite direction, solar irradiance is markedly lower in winter than in other seasons. This seasonal decline suggests that PV alone may be

insufficient to meet charging demand, particularly during the winter period.

4. CASE STUDY

In this case study, the sustainable supply of Bitlis's existing charging infrastructure using RES and a BESS is examined via a single-site demonstration at a selected transit and rest-facility location. On the supply side, the seasonal complementarity of wind and solar resources is considered; on the demand side, capacity is chosen to ensure service quality. The simulation framework was implemented in MATLAB, utilizing detailed meteorological datasets and validated engineering models for wind, solar, and battery systems. As a result, a capacity combination of 10 kW wind and 5 kW PV is proposed. The corresponding energy production and demand figures are presented in Table 4.

TABLE IV.
MONTHLY ENERGY PRODUCTION AND DEMAND DATA

Month	Wind Energy 10 kW (kWh)	Solar Energy 5 kW (kWh)	Total Energy (kWh)	Demand (kWh)	BESS Change (kWh)
January	2926	193.5	3119.5	3152	-32.5
February	2138	248.6	2386.6	3152	-797.9
March	6637	390	7027	2521	3708.1
April	4730	521.6	5251.6	2521	6438.7
May	2501	715.5	3216.5	2521	7134.2
June	1255	1018.5	2273.5	2521	6886.7
July	586	1035.4	1621.4	2521	5987.1
August	513	966.8	1479.8	2521	4945.9
September	671	860.6	1531.6	2521	3956.5
October	1172	566.6	1738.6	2521	3174.1
November	914	401.6	1315.6	2521	1968.7
December	1728	244	1972	3152	788.7

The table also reports energy demand values by summer and winter months. Finally, the monthly change in battery energy capacity is provided. According to these data, the lowest wind energy production from RES occurs in August at 513 kWh, while the highest occurs in March at 6,637 kWh. Similarly, the lowest PV energy production is 193.5 kWh in January, and the highest is 1,035.4 kWh in July. Examining monthly battery variation, the maximum stored energy is reached in May at 7,134.2 kWh. These results indicate that year-round service continuity can be maintained. Surplus generation periods are prioritized for storage, whereas deficits are supplied from the battery during resource-constrained periods. Considering battery efficiency and heating loads, a BESS of 8 MWh is envisaged. The 8 MWh capacity is determined by analyzing the monthly production demand balance, as detailed in Table 4 and Figure 8. The cumulative energy balance indicates a maximum storage requirement of approximately 7,134 kWh. To ensure year-round service continuity and to accommodate typical battery round-trip efficiency losses, this requirement is conservatively rounded up to 8 MWh. This sizing is based on typical meteorological year data; a probabilistic assessment incorporating inter annual variability is considered a direction for future work. Monthly energy production and demand are depicted in Figure 7.

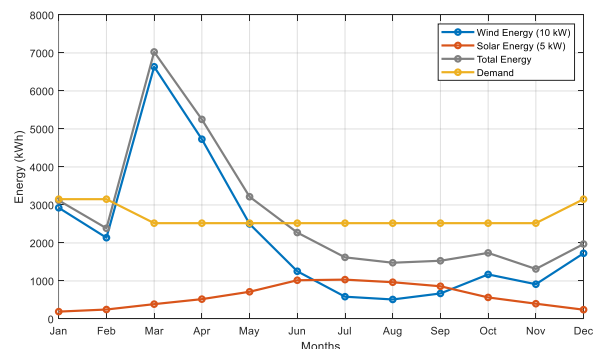


Figure 7. Monthly production and demand variation graphs

Here, blue denotes the energy produced by WPP, red the energy produced by PV, gray the total energy generated, and yellow the demanded energy. Consequently, the energy variation associated with the proposed battery energy storage system is presented in Figure 8.

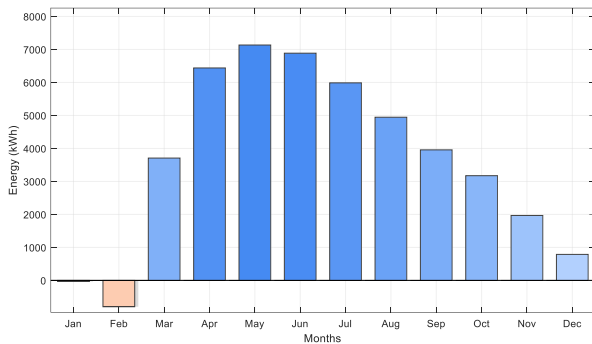


Figure 8. Cumulative battery energy variation

With the proposed energy storage system, year-round service continuity can be maintained, yielding a surplus of 788 kWh by year's end. This surplus can be utilized in emergencies or repurposed for other operational needs.

5. RESULTS

The monthly production–demand balance analyses conducted for the selected case-study station quantitatively demonstrate the impact of the seasonal behavior of hybrid WPP–PV generation and the associated storage requirement on year-round service continuity. Under the proposed configuration of 10 kW wind and 5 kW PV, total generation markedly exceeds demand in spring, with approximately 7,027 kWh in March and 5,252 kWh in April. By contrast, due to reduced wind speeds in summer, total generation declines; in July and August, production falls to roughly 1,621 kWh and 1,480 kWh, respectively, creating a noticeable deficit relative to demand. This profile indicates that surplus generation concentrates in spring, whereas deficits intensify in summer, thereby quantitatively supporting the conclusion that seasonality cannot be managed with a single resource and that a hybrid configuration is essential. The reflection of the monthly production demand gap on the cumulative battery energy balance further highlights the role of storage. Surpluses in March and April can be stored; in this regard, an 8 MWh storage capacity functions as a balancing mechanism to cover summer shortfalls.

Overall, the findings show that under seasonality dominated conditions, single source installations may conflict with the objective of service continuity; thus, the hybrid WPP,PV approach, considered together with storage, is not merely a technical preference but an operational necessity. Future work should incorporate higher temporal resolution (hourly) analyses and techno economic optimization to validate and tailor the proposed capacities to site-specific conditions, thereby strengthening investment decisions and concretizing a roadmap for sustainable charging infrastructure.

Beyond the specific context of Bitlis, these results are also informative for other mountainous or continental regions that exhibit similar meteorological regimes. In such climates, wind resources often dominate during colder months, while solar irradiance becomes the primary contributor in summer. This seasonal alternation supports hybrid designs that deliberately exploit wind–solar complementarity rather than relying on a single resource, and it justifies the use of sufficiently sized battery storage to bridge intra-seasonal generation deficits. Consequently, the design principles derived from the Bitlis case namely, asymmetric sizing of wind and PV in line with

seasonal dominance and storage-based balancing of summer shortages can serve as transferable guidelines for planning EV charging infrastructures in other regions with comparable topographical and climatic characteristics. In practical terms, the same modelling framework can be replicated for other provinces in Türkiye by compiling a province-level inventory of existing EV charging stations, obtaining local wind and solar resource data from the Global Solar Atlas and Global Wind Atlas, and reapplying the monthly demand and generation balance analysis to determine appropriate wind-solar-BESS capacities. This stepwise procedure makes the approach directly scalable from a single-province case study to a nationwide planning tool, and equally applicable to other regions worldwide that share similar climatic and topographical conditions. Replication and scaling of the proposed framework to other provinces or regions with similar climatic and topographic conditions require only the compilation of comprehensive station level inventories and localized high-resolution meteorological inputs; with these datasets the same methodological workflow can be applied without structural modification to yield comparable, policy relevant results.

From a policy and urban-planning perspective, these results highlight the necessity of prioritizing hybrid wind-solar-BESS configurations in regions facing seasonal resource intermittency for EV charging. The replicable, province-scale framework presented here offers national and regional decision-makers a tool to identify optimal locations and size hybrid systems, thereby informing infrastructure investment and incentive strategies for sustainable e-mobility. Policy and planning implications: The proposed framework directly supports regional decision making by enabling (i) site level prioritization of hybrid wind-solar-BESS deployments, (ii) evidence-based sizing of generation and storage to meet service-reliability targets, and (iii) the design of targeted incentive and procurement mechanisms that balance local supply autonomy with grid integration. We recommend that regional authorities adopt the framework as part of staged pilot deployments coupled with complementary data collection to validate operational performance and to refine investment and regulatory measures for scalable, low-carbon EV charging infrastructure.

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