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Designing and optimizing a hybrid microgrid supplying various electric vehicle charging modes

Çeşitli elektrikli araç şarj modları sağlayan hibrit bir mikro şebekenin tasarımı ve optimizasyonu

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Abstract

A microgrid system has been designed and optimized via hybrid optimization of multiple energy resources (HOMER) software for the electricity needs of Eskisehir Osmangazi University (ESOGU). The microgrid consists of photovoltaic (PV) and wind turbine (WT) units with utility grid connection and battery energy storage system (BESS). The microgrid also supplies energy to electric vehicle (EV) charging units. The combination of EVs and renewable microgrids make a major contribution to the clean energy transition of the global energy system. It also minimizes the cost of energy (COE) and EV charging. Before analyzing the EV loads, a proper hybrid combination of the microgrid was optimized. The comparison and analysis of the proposed systems were performed according to their reliability, economic and environmental impact. The financial analysis of the winning microgrid system was carried out and its performance assessed throughout the duration of the project. Deferrable and on-demand EV charging modes were proposed in this study. To see the impact of EVs on the microgrid, various scenarios were created and applied to the design. The aim was to find a suitable charging method that uses mostly the renewable energy sources to minimize the cost of electricity while protecting the environment. This study demonstrates the importance of smart charging and how it manages charging sessions by leveraging renewable resources and charging only when electricity is at the lowest cost. The result also shows that the cost of the electricity bill of the investigated area is reduced by 36% by using the hybrid microgrid.

Keywords: Electric vehicle, Deferrable EV charging, Hybrid microgrid, On-demand EV charging, Optimization, Renewable energy.

Öz

Eskişehir Osmangazi Üniversitesi'nin (ESOGU) elektrik ihtiyacı için çoklu enerji kaynaklarının hibrit optimizasyonu (HOMER) yazılımı ile bir mikro şebeke sistemi tasarlanmış ve optimize edilmiştir. Mikro şebeke, elektrik şebekesi bağlantılı ve batarya enerji depolama sistemine (BESS) sahip fotovoltaik (PV) ve rüzgâr türbini (WT) ünitelerinden oluşmaktadır. Mikro şebeke ayrıca elektrikli araç (EV) şarj ünitelerine enerji sağlamaktadır. EV'ler ve yenilenebilir mikro şebekelerin kombinasyonu, küresel enerji sisteminin temiz enerji geçişine büyük katkı sağlamaktadır. Ayrıca enerji maliyeti (COE) ve EV şarjını da en aza indirmektedir. EV yüklerini analiz etmeden önce, mikro şebekenin uygun bir hibrit kombinasyonu optimize edilmiştir. Önerilen sistemlerin güvenilirliği, ekonomik ve çevresel etkilerine göre karşılaştırılmış ve analizleri yapılmıştır. Kazanan mikro şebeke sisteminin finansal analizi yapılmış ve proje süresince performansı değerlendirilmiştir. Bu çalışmada ertelenebilir ve isteğe bağlı EV şarj modları önerilmiştir. EV'nın mikro şebeke üzerindeki etkisini görmek için çeşitli senaryolar oluşturulmuş ve tasarıma uygulanmıştır. Amaç, çevreyi korurken elektrik maliyetini en aza indirmek için çoğunlukla yenilenebilir enerji kaynaklarını kullanan uygun bir şarj yöntemi bulmaktır. Bu çalışma, akıllı şarjın önemini ve yenilenebilir kaynaklardan yararlanarak ve yalnızca elektrik en düşük maliyette olduğunda şarj ederek şarj oturumlarını nasıl yönettiğini göstermektir. Sonuç ayrıca, hibrit mikro şebeke kullanılarak incelenen alanın elektrik faturasının maliyetinin %36 oranında azaldığını göstermektedir.

Anahtar kelimeler: Elektrikli araç, Ertelenebilir EV şarjı, Hibrit mikro şebeke, İsteğe bağlı EV şarjı, Optimizasyon, Yenilenebilir enerji.

1 Introduction

There has been a growing interest in hybrid renewable energy systems leading to an increase in microgrid constructions all around the globe. The reason for preferring hybrid systems over single-source systems is their increased reliability and higher energy productions. The most frequently used hybrid renewable energy sources are solar and wind energy [1],[2]. Solar and wind electric energy production systems have relatively low installation costs and they accompaniment one another in the supply of energy. Neither solar nor wind energy is always available, and the efficiency of their production depends on weather conditions. Integrating PV and WT systems fills the blank and improves production quality. A review and analysis of 550 papers published on the hybrid PV and WT systems from 1995 to 2020 has been presented by Mazzeo et al. [3].

Microgrids are the optimal solution for smarter, reliable, and more efficient energy operations [4]. A microgrid consists of various energy sources and loads that are dispersed but interconnected inside a zone with clearly defined electrical borders. The microgrid is a controllable entity in comparison to the utility grid [5]. To avoid the generation imbalances and low-quality operations that conventional grids characterize, more reliable and cost-effective systems like microgrids were developed. Microgrids enable easy access to renewable sources

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and lower greenhouse emissions, and they reduce the dependence on the grid. Not only remote areas but educational campuses and large building infrastructures recall the need for microgrid systems to optimize their power consumption and reduce the cost that is spent on electric utility billing.

Today, renewable energy sources are used not only for utility but also for charging EVs in the transportation sector. The global EV market shows potential growth in the last few years. In Turkey, EV sales are growing day by day [6]. In the next decade, electric cars in Turkey will reach two-and-half million in number representing about 10% of the total number of vehicles. In the same decade, battery operated and plug-in hybrid EVs will be as much as 55% of all vehicle sales according to the research carried by Shura Energy Transformation Centre [7].

A charging point or charging station, is required for most EVs be it a battery electric vehicle or plug-in hybrid electric vehicle (PHEV). The charging points are normally connected to the electric grid, microgrids, or other renewable energy sources. In order to perform a reliable charging system, adequate charging infrastructure that has strong coordination with the grid must be found. Presumably the owner of the vehicle could establish a charging point at his residence, yet it is not going to allow the vehicle to travel far. The public charging points should be carefully installed to provide optimum service to the working EV [8]. The EV battery charging in most lands is less costly than the equivalent fuel fills for traditional vehicles despite the variations in prices of electricity and petroleum.

While some companies in Turkey work on EV-based sub-components such as motor drives and battery managers, some companies work on EV charging groundwork. Gönül et al., lists five largest domestic EV charging station companies. These companies operate 627 EV charging stations and attempt to advance their capabilities and service [9]. Due to its developed automotive industries and growing technology Turkey has a potential market to produce charging infrastructures. Also, universities and public facilities take part in EV-related research activities.

Integration of hybrid renewable microgrids and EVs are attracting the attention of many researchers as recent studies show. Many of these studies focus on the way of optimization or scheduling these systems. In order to plan a microgrid's ideal power performance, Can et al. [10] employed a metaheuristic approach. Jin et al. [11] improved a hierarchical management for the development of microgrids by accounting for virtual storage systems and PHEVs. The improvement of EV integration with smart grids has been reviewed by Erdogan et al. [12] in a different study on EVs and the interaction of smart grids. Mwasilu et al. [13] looked at the impacts of several EV charging techniques in a grid-tied PV microgrid system. To address their problems, designers use a variety of optimization strategies. These techniques can be computational ones like algorithms or tools like optimization software. Models of off-grid and on-grid renewable energy systems were created by Panhwar et al. [14]. They used HOMER software to calculate the energy requirements, optimize both systems, and conduct their economic analyses. To supply reliable power for a rural village, a hybrid microgrid utilizing a WT, PV, and a diesel-fueled generator is designed by Astatike and Chandrasekar. The performance of the system and the analysis were done using HOMER [15].

A technological and economical way for optimizing a microgrid system using mixed integer linear programming was presented by Ahmet J. et al. [16] The benefits of regulating the intermittency and volatility of distributed source generation, as well as lowering load peaks, are discussed in this study. Using a broad algebraic modeling approach, linear programming is used to solve the cost function. The simulation and optimization of the results were presented using HOMER software. Lee et al. [17] designed an energy controller for microgrid that can schedule charging or discharging activity of EVs seeking to reduce the microgrid's peak load and maximize the integration of renewable energy. Likewise, the impact of PHEV charging demand on microgrids' ideal short-term scheduling using backtracking search optimization was examined by Li, Yong et al. [18]. Three charging schemes smart, controlled, and uncontrolled were compared and the results demonstrated that this method outperformed other methods. It was also demonstrated that the PHEV charging requirement might increase the microgrids' overall operating costs. However, a clever charging approach might reduce this effect. In addition to that, managing smart microgrids can be used for solving integration problems when it comes to unpredictable loads as Salvatti et al. [19] proposed a microgrid management technique that uses a common AC bus to enable interaction between EVs and microgrid by controlling factors like economic and supply quality. Though the optimization methods can be in different techniques, some researchers prefer linear or non-linear optimization techniques. Pierre et al. [20] used nonlinear control strategy based on the Lyapunov approach to assure the voltage stability of DC microgrid and EVs together. Several EV charging strategies have been presented to proof the effectiveness of this control system.

A renewable energy microgrid related architecture and control schemes utilized in EV charging stations were presented by Savio Abraham [21]. The study underlines the significance of various charging station architectures with the power converter topologies comparing the energy management, control schemes, and charging converter controls of charging stations. [22] used mixed-integer linear programming method to solve the real time operation problem of microgrid based EVs. The aim of the study was to minimize the total COE consumed by the EVs and other loads. The periodic arrival and departure of EVs were taken into consideration when optimizing the COE.

From various literature, it can be observed that the interaction of renewable microgrids and EVs is important for both environmental protection and EV users in terms of cost and simplicity. In this research work, firstly the components of a hybrid microgrid is modeled by using a simple algebraic modeling method aiming to reduce the utility bill of ESOGU located in Turkey using converter and exploiting the renewable sources followed by two EV charging modes and their charging optimization analysis have been performed. Among investigated charging modes, the effective mode for both users and the grid can be accessed through the result of this study.

The modeling and the design of the microgrid system is described in Section 2. Section 3 presents the optimization tool used in this study while Section 4 shows the results obtained during the study. Section 5 concludes the paper with the benefits of the designed system.

2 Modeling of the microgrid system

Since microgrids contain one or more generation sources, modeling each component is necessary for coherent and well-organized system design. The choice of hybrid sources is also important at this stage. Factors like the wind and solar irradiation potential and the cost of installation play an important role in deciding on the suitable hybrid combination. PV-WT, PV-diesel, WT-diesel, and PV-WT-diesel are commonly used hybrid combinations. Since these renewable sources depend on atmospheric and weather conditions, such hybrid combinations require some auxiliary energy generation units or storage units for an uninterrupted supply [3].

PV and WT energy sources are used in the system considered for this study. By considering the available resource of the studied area, a grid-connected PV and WT microgrid system is designed. EV charging points are also part of the microgrid. ESOGU campus is the area of interest in this study and located in Eskisehir city with 39°45.1' N latitude and 30°29.0' E longitude.

2.1 The primary load

The main load used is a total load of one year's electricity consumption of the ESOGU campus. The average annual energy consumption per day is 49286 kWh and the average power is 2053.6 kW. The peak power is 4552.2 kW and the load factor is 0.45. Peak demand occurs in July. Figure 1 shows monthly load profile of ESOGU campus.

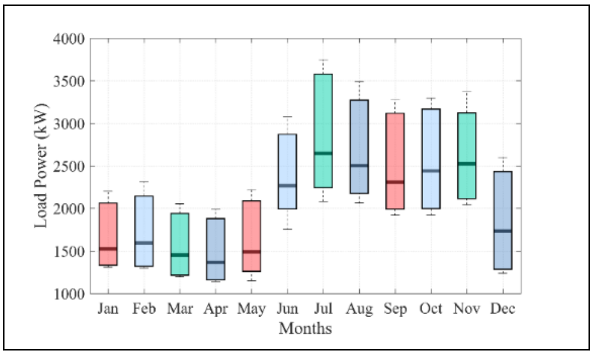


Figure 1. Monthly load profile of ESOGU campus.

2.2 PV system

The PV production in this system is approximately 32% of the total system generation. During modeling, the availability and the cost of each component are main factors to set the percentages of components in the system. Turkey's geographical location is highly satisfactory for the utilization of solar energy. The PV output power is calculated by Eq. (1) [23].

$$P_{PV} = Y_{PV} \times f_{PV} \times \left(G_T / G_{T,STD}\right) \times \left[1 + \alpha_p \times \left(T_c - T_{c,STD}\right)\right] \tag{1}$$

In Eq. (1), Y_{PV} is the rated PV output power; f_{PV}, the PV derating factor; G_T, the incoming solar radiation; $G_{T,STD}$, the standard incoming radiation; α_p, the temperature coefficient; T_c, the PV cell temperature, and $T_{c,STD}$, the PV standard cell temperature for test conditions. The scaled annual average solar radiation for the location of the PV arrays is found to be 4.26 kWh/m²/day. Figure 2 shows the daily insolation as well as the clearness index for the studied area.

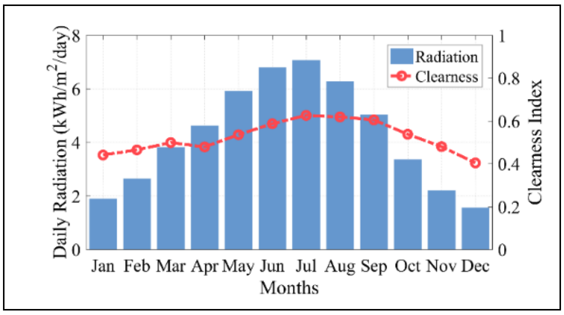


Figure 2. Averaged daily solar radiation and clearness index for the location of PV system.

2.3 Battery energy storage system

Since renewable energy sources are unpredictable, a backup energy system is necessary for a reliable and sustainable power system. This BESS is for the partial fulfillment of the electrical demand, not all of it. The energy stored in the battery is represented by the state of charge (SOC). SOC is calculated by Eq. (2) [24].

$$SOC\,(t+1) = SOC(t) + \eta_{Batt} \times \left[P_{Batt}(t)/V_{bus}\right] \times \Delta t \tag{2}$$

In Eq. (2), $SOC(t)$ and $SOC\,(t+1)$ are the amounts of charge stored in the battery at time interval t and $t+1$, η_{Batt} is the battery efficiency, and $P_{Batt}(t)$ is the average battery charging power during the time interval Δt. The battery is not completely drained to extend its lifetime. The discharge of the battery is handled via the depth of discharge (DOD) is given by Eq. (3) [25]. The charge in the battery is kept between two limit values: SOC_{min} is the lower limit during discharging, and SOC_{max} is the upper limit for charging.

$$SOC_{min} = (1 - DOD) \times SOC_{max} \tag{3}$$

2.4 WT system

Wind energy is also a competitive renewable source for electricity production. The geographical location of the studied area offers extensive wind energy potential. The wind production in this system is approximately 22% of the total system generation. The WT output power is calculated by Eq. (4) [26].

$$P_{WTG} = \left(\rho/\rho_o\right) \times P_{WTG,STP} \tag{4}$$

In Eq. (4), P_{WTG} is the actual WT output power, ρ is the air density at the location, and ρ_o is the standard air density (1.225 kg/m³), and $P_{WTG,STP}$ is the WT output power at standard temperature and pressure. The average annual wind speed based on the longitude [30.25°E] and latitude [39.75°N] of the study area is shown in Figure 3.

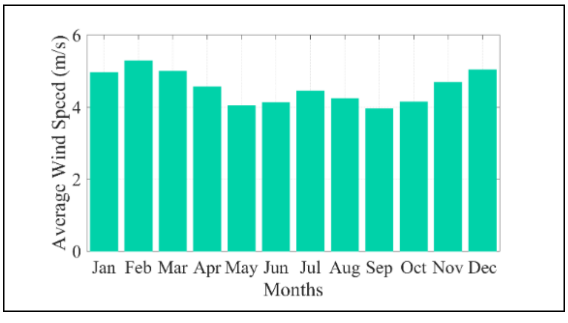


Figure 3. Average wind speed of studied area.

2.5 Bidirectional converter

This hybrid system is a combination of AC and DC power, so that a bidirectional converter is placed between the AC and the DC buses. The power output of the inverter side can be calculated by Eq. (5) [27].

$$P_{out} = P_{in} \times \eta_n \tag{5}$$

In Eq. (5), P_{out} is the AC output power; P_{in} is the DC input power, and η_n is the efficiency of the inverter which is taken as 95%.

2.6 EV charging modes

EVs have various charging levels and modes. The charge level is also referred to as the charge rate, while the charge mode refers to the contact between the vehicle and the charging station. There are four modes of charging. Mode-1 is a slow mode charging from a regular socket. Mode-2 is also a slow mode charging with some EV protection arrangement. Mode-3 can be slow or fast mode charging with control and communication protocol (also known as smart charging). Mode-4 is a DC fast charging mode. The details of EV charging modes and levels are described by Bahrami [28].

Deferrable/smart and on-demand/fast charging modes are presented in this study. The deferrable charging mode of electric vehicles enables users to give priority the use of renewable energy by planning charging to use grid power at the most economical time. Additionally, on-demand mode is a fast method of charging EVs for a more effective charging solution, enabling clients to charge their EVs in a very short time instead of long hours. To establish the EV load, the most commonly used EV models in the study area are taken into account. Different scenarios are created to examine the difference between deferrable and on-demand EV charging modes.

2.7 Utility grid

According to the location of the study area: the demand charge is \$0.098697 and the sell-back rate is also \$0.098697. These values were obtained from the Turkey's Energy Market Regulatory Authority energy sell rates.

3 Optimization method and assessment criteria of the microgrid system

In every design, a proper optimization method is necessary for the reliability and economic feasibility of the system. So many techniques are available for optimal sizing of hybrid microgrids. HOMER is one of the most frequently employed software in the optimization of renewable sources. It can be used in the design of stand-alone and distributed generation power systems with or without grid connection. It can also provide technical and financial evaluation for the designed power systems [29]. It brings together a variety of energy sources, both conventional and renewable, analyzes them automatically, and then optimizes the data so that it can be used for investing and other activities like decision-making. HOMER analyzes for sensitivity, optimizes, and simulates. The configuration of system components and their modeling are chosen during the simulation operation in order to assess the technical and financial viability of the micropower systems. The most appropriate system configuration is chosen during the optimization process, and the net present cost (NPC) method is used to reach an optimal solution. As a third step, it offers a sensitivity analysis to show the factors and unpredictability that the designer cannot manage in the long term. In this work, the hybrid microgrid is designed and optimized using the HOMER Grid. With HOMER Grid, a new version of the program, you can create distributed, behind-the-counter, and grid-connected systems. Additionally, it adds the capacity to model electric vehicles, which was missing from earlier HOMER software iterations. NPC and levelized COE economic meters are taken into consideration in this design. While COE determines the system's overall cost of energy during its lifespan, NPC includes all recurring expenses and income for the duration of the system, from original installation costs to the salvage value of the system. NPC is determined using Eq. (6) [30].

$$NPC = \sum_{t=0}^{T} C_{cap,n} + C_{om,n} + C_{rep,n} + C_{fuel,n} - \left(R_{s,n} + R_{g,n}\right) \tag{6}$$

In the expression, T is for the lifetime of the project. $C_{cap,n}$ is the cost of capital in year n. $C_{om,n}$ is the maintenance and operation cost at year n. $C_{rep,n}$ is the replacement cost on year n. $C_{fuel,n}$ is the fuel cost at year n. While $R_{s,n}$ and $R_{g,n}$ respectively are salvage and grid revenues from year n. The COE is calculated by Eq. (7) [30].

$$COE = C_{tot}/E_{tot.load} \tag{7}$$

In the expression, C_{tot} stands for the total cost of the project each year, and $E_{tot.load}$ is the entire electrical load in a particular year. In other words, COE is the ratio of all cost of production to the overall electrical load.

The return on investment (ROI) is also considered in this design which is the yearly cost savings relative to the initial investment. ROI is calculated by Eq. (8).

$$ROI = \sum\nolimits_{i=0}^{R_{proj}} \left(C_{i,ref} - C_i\right) \Big/ \left(R_{proj} \times \left(C_{cap} - C_{cap,ref}\right)\right) \tag{8}$$

In Eq. (8), $C_{i,ref}$ is the nominal annual cash flow for base (reference) system, C_i is the nominal annual cash flow for current system, R_{proj} is the project lifetime in years, C_{cap} is the capital cost of the current system, and $C_{cap,ref}$ is the capital cost of the base (reference).

HOMER also calculates the internal rate of return (IRR) by determining the discount rate that makes the present value of the difference of the two cash flow sequences equal to zero.

4 Results and discussion

In this section, the HOMER simulation results of the recommended systems are presented. System design comprises two main sections: one part is the microgrid system which itself contains five components as mentioned before, and the other part is the EV charging stations. The optimization results were then analyzed to find the most appropriate system for both consumption and EV charging. During the analysis, three cases of microgrid system were examined and compared to see whether they are economically, environmentally and reliably effective. After deciding the proper hybrid system, the EV charging modes were analyzed, and their impact on the microgrid has been evaluated. To do this, three scenarios were created and tested on both charging modes separately and simultaneously.

4.1 Technical and economic design parameters of the microgrid components

The economic design parameters and technical specifications of the components of the microgrid system are shown in Table 1.

4.2 Design considerations of EV charging modes

In this study, each of the chosen vehicles constitute 20% of the total EV population. The average estimated on-demand EV charger load, is 1089 kWh/day and the deferrable load is 868 kWh/day. The load is created randomly in the HOMER during modeling of the two charging stations. Table 2 displays the deferrable EV charger input data. The output power of the charger is 22 kW having 10 chargers. The average connection time is 8 hours and the average number of daily sessions is 20.

The maximum charging power and the required energy per EV are accessed through EV database [29]. The same EV models are used in modeling the on-demand station. The energy needed per EV stays identical, but the charging rate is increased in this mode. Table 3 presents the on-demand EV charger input data. The output power of the charger is 150 kW having 10 chargers. The average connection time is 1 hour and the average number of daily sessions is 20.

Table 1. Design parameters of components and units of hybrid microgrid.

Microgrid Component	Parameter Description	Value	Unit
Grid	Grid power price	0.098697	$/kWh
	Grid sell back price	0.098697	$/kWh
PV	Panel type	Flat plate	-
	Rated capacity	5000	kW
	Efficiency	20	%
	Capital cost	2750	$/kW
	Replacement cost	2750	$/kW
	O&M cost	7.5	($/kW)/yr.
	Lifetime	25	yr.
WT	Rated Capacity	2000	kW
	Capital cost	3000	$/kW
	Replacement cost	3000	$/kW
	O&M	300	$/kW
	Lifetime	20	yr.
Battery	Battery type	Li-ion	-
	Nominal capacity	1000	kWh
	Capital cost	700,000	$/batt.
	Replacement cost	700,000	$/ batt.
	O&M cost	10,000	($/year)/ batt.
	Initial state of charge	100	%
	Minimum state of charge	20	%
	Lifetime	15	yr.
Converter	Capital cost	300	$/kW
	Replacement cost	300	$/kW
	O&M cost	10	$/kW/year
	Lifetime (inverter input)	15	yr.

Table 2. The input data of the deferrable EV charger.

Model Name	Percentage of EV Population (%)	Maximum Charging Power per EV (kW)	Average Charging Duration (hrs.)	Average Required Energy (kWh)
Jaguar I-Pace	20.0	16.5	10.0	90.0
Renault Zoe	20.0	22.0	3.0	52.0
BMW i3	20.0	11.0	4.5	43.0
Mercedes EQC 400 4MATIC	20.0	11.0	8.5	85.0
Hyundai Kona	20.0	11.0	7.0	64.0

Table 3. The on-demand EV charge input data.

Model Name	Percentage of EV Population (%)	Maximum Charging Power/EV (kW)	Average Energy Required (kWh)	Average Charging Time (min)
Jaguar I-Pace	20.0	104.0	90.0	44.0
Renault Zoe	20.0	46.0	52.0	56.0
BMW i3	20.0	49.0	43.0	36.0
Mercedes EQC 400 4MATIC	20.0	112.0	85.0	35.0
Hyundai Kona	20.0	77.0	64.0	44.0

4.3 Hybrid combinations of the microgrid with and without energy storage

Two hybrid combinations are proposed. The first combination is a grid-connected PV and WT systems (Case 1). The second combination is a grid-connected PV, BESS, and WT systems (Case 2). A comparison is typically performed based on economic, environmental impact, and the reliability of the systems as shown in Table 4. From the economic perspective, Case 1 is more economical than Case 2 due to the cost of the BESS in Case 2. However, Case 2 is more environmentally friendly and more reliable than Case 1. The reliability comes from the availability of the BESS. The purpose of designing hybrid systems is to enhance the overall system performance while maintaining a clean environment. For that reason, with a little bit of difference in economics, Case 2 wins over Case 1. The structure of the designed microgrid is shown in Figure 4. The production of the system and the load served are as follows.

Table 4. Economic comparison, and reliability and the environmental impact of the system cases.

	Variables	Case 1	Case 2	Unit
Costs, Savings, and Economic Metrics	Capital expenses	6,667,377	7,354,081	$
	Operation expenses	894,061	935,351	$
	Annual total savings	390,012	348,722	$
	Annual utility bill savings	452,300	450,738	$
	Annual energy charges	799,831	801,393	$/yr.
	Discounted payback time	9.5	15.1	yrs.
	Simple payback time	7.1	9.0	yrs.
	LCOE	0.070	0.075	$/kWh
	IRR	12.68	8.30	%
	NPC	18,225,360	19,445,850	$
Reliability & Environmental Impact	CO2 emissions	6,125.9	5,991.9	metric ton/yr.
	Degree of reliability	Reliable	More reliable	-

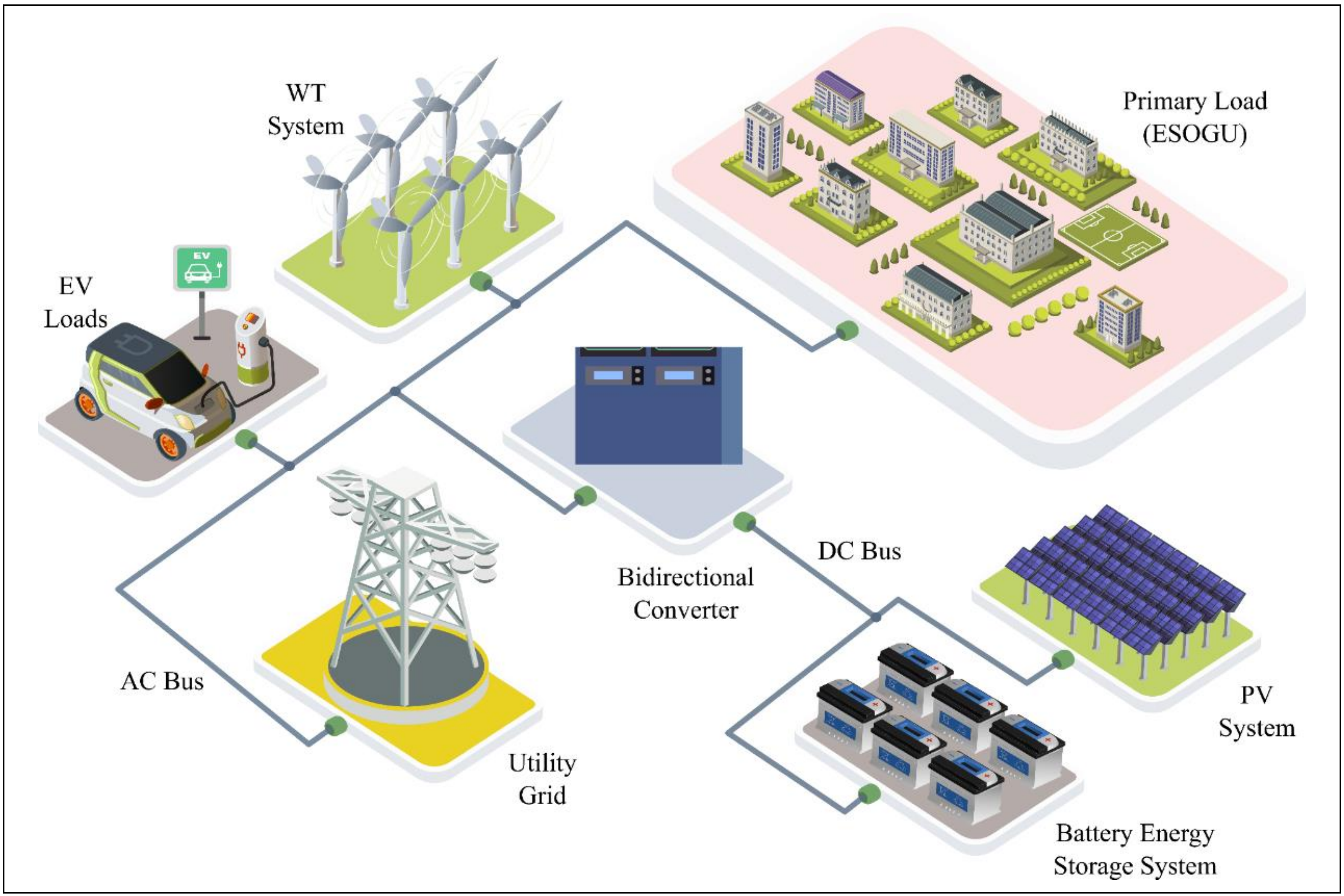


Figure 4. Structure of the designed microgrid.

The output characteristics of system components obtained through HOMER are presented first. This microgrid system's total production is 20,512,000 kWh/yr. The output power of system components is presented in Table 5. The overall production of the PV array is 6,448,371 kWh/yr with a rated capacity of 5 MW. Factors like temperature and seasonal variations affect the PV output. In this model, the effect of temperature on power is estimated as -0.5 %/°C. The capacity of the BESS is 1 MWh, and its lifetime throughput is estimated to be 2,861,063 kWh. The WT system produces 4,582,721 kWh/yr with a nominal capacity of 2 MW. Converter capacity is 3,014 kW with an output of 843 kW at the rectifier side and 3,014 kW on the inverter side.

Table 5. Outputs of system components.

System Component	Variables	Value	Unit
PV system	Capacity	5,000	kW
	Average Output power	736	kW
	Average Output energy	17,667	kWh/d
	Factor of capacity	14.7	%
	Overall Production	6,448,371	kWh/yr.
	Converter	5,000	kW
BESS	Autonomy	0.390	hr.
	Wearing Cost	0.246	$/kWh
	Capacity	1,000	kWh
	Usable Capacity	800	kWh
	Lifetime Output	2,861,063	kWh
	Expected Lifetime	11.8	yr.
WT system	Capacity	2,000	kW
	Average Output	523	kW
	Factor of capacity	26.2	%
	Overall Production	4,582,721	kWh/yr.
Bi-directional system converter	Inverter/Rectifier Capacity	3,014/3,014	kW
	Inverter/Rectifier Avg. Output	690/4.57	kW
	Inverter/Rectifier Min. Output	0/0	kW
	Inverter/Rectifier Max. Output	3,014/843	kW
	Inverter/Rectifier Factor of capacity	22.9/0.152	%

Figure 5 shows how generation sources provide electricity and how they support the load. According to information on campus energy consumption, the principal AC load served annually is 17,989,554 kWh. The estimated annual grid sales come to 1,340,899 kWh. The EV chargers provide 714,639 kWh each year. 4811 kW are used at peak load. The biggest renewable contribution comes in March, as seen in Figure 6, and the system's overall renewable share is 52.7%.

4.4 EV charging scenarios

Besides the load served to the campus, 3.5% of the total generation is served to the EV loads. Three scenarios of EV charging modes are presented in Tables 6 through 8. In the first scenario shown in Table 6, a total of 100 vehicles with 5 different models each representing 20% of the total population were applied on both on-demand and deferrable charging modes simultaneously under the same conditions to see the impact of EVs on the microgrid clearly. Applying both charging modes at a time will make EVs consume more energy from the grid than renewable sources. Our aim is to minimize energy purchased from the grid and maximize the renewable energy fraction.

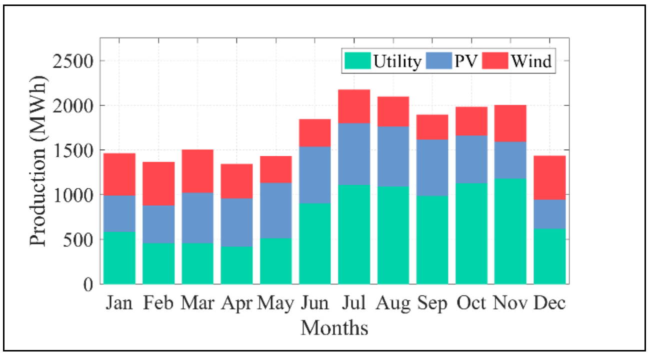


Figure 5. Monthly electrical production of generation sources.

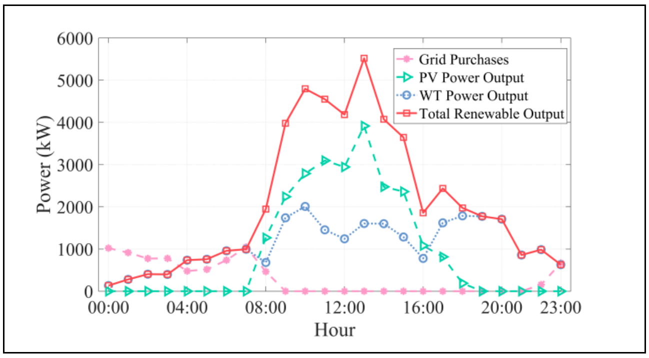


Figure 6. Load profile of the peak day.

In the second scenario shown in Table 7, the same EV models-each one representing 20% of total population-were used to apply the on-demand charging mode. It is observed that the NPC is increased by 1% compared to the deferrable mode. Also, the renewable fraction is decreased by 1% which makes this mode less environmentally friendly compared to the deferrable mode. The effect of EV loads on the microgrid is reduced from 3.5 percent to 2 percent when just the on-demand charging method is used.

In the third scenario shown in Table 8, the same EV models-each one representing 20% of total population-were used to apply on the deferrable charging mode. It is observed that the NPC is decreased by 1% when the deferrable mode is applied. Also, the renewable fraction is increased by 1%. Since this mode harvests the renewable sources more, it makes this mode cost-effective for users. The effect of EV loads on the microgrid is reduced from 3.5 percent to 1.5 percent when just the deferrable charging method is used.

4.5 Discussion

The load served to the EVs is given in Table 9. Also, the graphical representations of deferrable and on-demand EV loads are given in Figure 7(a) and Figure 7(b) respectively.

Table 6. EV charging scenario I.

EV Charging Mode	Daily Profile (kWh/day)	Charge Power (kW)	Average Charge Duration Per EV (hr.)	Number of Vehicles	NPC ($M)	Renewable Fraction (%)
Deferrable	868	22	8	100	19.4	52
On-demand	1089	159	1	100		

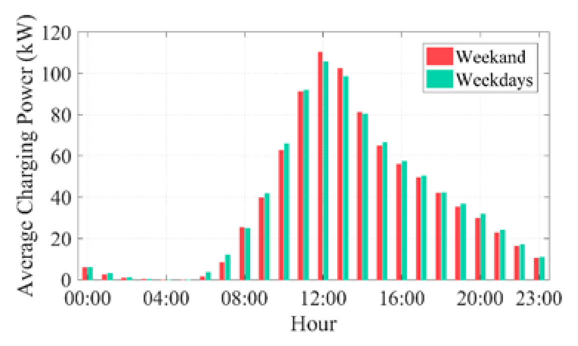
Table 7. EV charging scenario II.

EV Charging Mode	Daily Profile (kWh/day)	Charge Power (kW)	Average Charge Duration Per EV (hr.)	Number of Vehicles	Impact on NPC (%)	Renewable Fraction (%)
On-demand	1089	159	1	100	1% increase	1% decrease

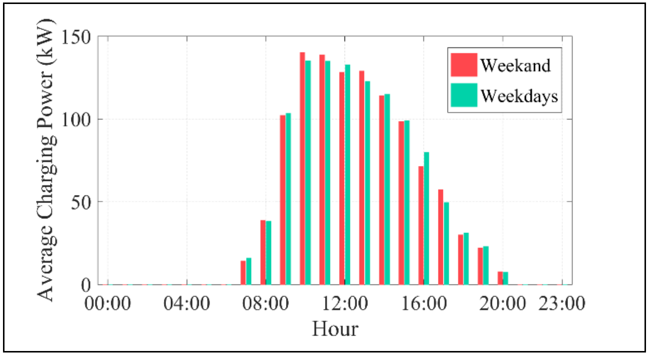
Table 8. EV charging scenario III.

EV Charging Mode	Daily Profile (kWh/Day)	Charge Power (kW)	Average Charge Duration Per EV (hr.)	Number of Vehicles	Impact on NPC (%)	Renewable Fraction (%)
Deferrable	868	22	8	100	1% decrease	1% increase

The on-demand EV charger has an annual energy usage of 397,399 kWh and a peak load of 304 kW. In this configuration, 10 chargers provide 20 charging sessions each day. The maximum output power that each of these chargers can handle is 150 kW. The average charge time for the on-demand type is less than an hour, and it functions as a rapid charger. In this setting, there is no missed session. The deferrable EV charger, on the other hand, uses 317,240 kWh/year with a maximum capacity of 160 kW. In this mode, there are 10 chargers and 13 charging sessions per day. These chargers can each handle a maximum output capacity of 22 kW. Due to the fact that there were no available chargers, an average of 7 potential users per day abandoned their EVs uncharged.



(a): Deferrable.



(b): On-demand.

Figure 7. Deferrable and on-demand EV load served.

Comparing the EV charging modes, it can be observed from Table 9 that the on-demand charging mode has higher demand than the deferrable mode and has more impact on the grid. The same EV models were used in both charging modes to compare their differences, and the amount of energy needed per EV remained constant. However, the load served grows in direct proportion to the output power of the charger and the rate of charging, which increased demand for the on-demand type. The deferrable EV charging option functions as smart charging and only charges during times of low electricity cost, making it more affordable and appealing to users. When using this charging mode, the microgrid is affected by deferrable mode to the extent of 1.5% of the total load provided to the EVs.

Table 9. The load served to the EV chargers.

Station Details	EV Charger		Unit
	Deferrable	On-Demand	
Max. charger power output	22	150	kW
Average time to charge an EV	8	1	hr.
Energy served annually	317,240	397,399	kWh
Maximum power	160	304	kW
Sessions daily	13	20	-
Sessions annually	4756	7308	-
Daily sessions missed	7	0	-
The microgrid's Impacts	1.5	2	%

4.6 Sensitivity analysis

In this last section, sensitive variables were added to the model to make the modeling more realistic and to show the uncertainties of some variables like charging duration of the vehicles and day-to-day variation of the EV loads as shown in Table 10. The results of the third scenario were used to apply the sensitive variables since the deferrable mode remains the effective charging mode for users. 10% variation in both the charge duration and day-to-day variability among vehicles would make the daily profile change from 868 kWh/day to 916 kWh/day. Increasing these values to 20% will result the daily profile to change from 868 kWh/day to 931 kWh/day. Likewise, if the values of variables are increased to 30%, the daily profile continues to change from 868 kWh/day to 963 kWh/day. Also, the effects of these changes on the overall NPC and the renewable fraction are recorded as presented in Table 10. Lastly, this system has a total NPC of $19,445,848 and has an average annual energy bill saving of $450,738.10. The payback period is 9 years. Table 11 summarizes the overall system costs.

Table 10. Sensitivity analysis for deferrable EV charging.

EV Charging Mode	Charge Duration Variability (%)	Day-to-Day Variability (%)	Daily Profile (kWh/Day)	Impact on Overall NPC (%)	Renewable Fraction (%)
Deferrable	10	10	916	2.0% decrease	53.5
	20	20	931	1.5% decrease	53.5
	30	30	963	1.0% decrease	53.4

Table 11. Cost summary of the system.

Component	Capital Cost	Replacement Cost	O&M Cost	Fuel Cost	Salvage Cost	Total NPC	Unit
WT system	3,000,000	956,422	387,826	0.00	539,005	3,805,242	$
BESS	700,000	537,351	129,275	0.00	148,459	1,218,168	$
PV system	2,750,000	0.00	96,956	0.00	0.00	2,846,956	$
Grid	0.00	0.00	10,360,015	0.00	0.00	10,360,015	$
Converter	904,081	383,578	0.00	0.00	72,193	1,215,466	$
Overall system	7,354,081	1,877,352	10,974,072	0.00	759,657	19,445,848	$

5 Conclusion

The cost of electricity is a huge problem especially in large buildings where electricity consumption is very high. Instead, using renewable energy sources is a solution for electricity cost reduction. This study provides the optimization of a hybrid microgrid that contains solar and wind power generations with a utility grid to reduce the annual utility bill of ESOGU. HOMER Grid has been used for the simulation and optimization of the designed system. Exploiting the renewable energy sources in the microgrid EV charging modes have been also modeled. Deferrable EV charging mode that works as smart charging and on-demand EV charging mode that works as fast charging were modeled in this study. As a result, the designed microgrid system reduces the electricity bill of the studied area by 36%. Moreover, when compared to the on-demand EV charging mode, the deferrable/smart EV charging mode has been found to be the more effective charging system for both users and the microgrid. The study shows that smart charging has benefits for EV owners and charge suppliers in terms of charging safety, billing system, grid stability, and cost of charging. Using the deferrable mode, the impact of EVs on the microgrid has been reduced to 1.5%.

6 Author contribution statements

Farhia Adullahi MOHAMUD and İpek ÇETİNBAŞ: conceptualization, software, methodology, writing-original draft, formal analysis, validation, visualization. Mehmet DEMİRTAŞ and Hasan Hüseyin ERKAYA: supervision, methodology, review, editing, conceptualization, formal analysis.

7 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person or institution in the article prepared.

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