OPTIMIZATION AND TECHNO-ECONOMIC ANALYSIS OF ELECTRIC VEHICLE CHARGING SYSTEMS IN RENEWABLE ENERGY-BASED MICROGRIDS ON UNIVERSITY CAMPUSES

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Abstract

This study presents a comprehensive optimization and techno-economic analysis of electric vehicle (EV) charging systems integrated into renewable energy–based microgrids within university campuses. Using the HOMER Grid software, hybrid configurations combining photovoltaic (PV) panels, wind turbines, diesel generators, and battery storage systems were simulated under 8760-hour real meteorological and load data for the Yalova University campus. Five distinct EV charging scenarios—Highway Charger (Level 3, On-Demand), Multifamily Residential Charger (Level 2, On-Demand), Office Charger (Level 2, Deferrable), Public On-Demand Charger, and Overnight Fleet Charger (Level 3, Deferrable)—were evaluated under nine system configurations (S1–S9) to determine the optimal design balancing cost, energy independence, and environmental impact.

Among the simulated cases, Scenario S2 (Solar + Storage + Grid) achieved the best overall performance, with a net present cost of $860,470, LCOE of $0.0452/kWh, and an internal rate of return (IRR) of 85%. The system demonstrated a 99% renewable fraction, reducing annual CO_2 emissions by over 60% compared with the base grid-dependent configuration. Economic assessments revealed substantial operational savings, including annual utility bill reductions exceeding $53,000 and a simple payback period of approximately 1.2 years.

The Highway Charger (Level 3) exhibited the highest annual energy savings and confirmed the feasibility of renewable-based fast-charging solutions, while Level 2 chargers achieved moderate investment returns with payback periods below five years. The integration of PV and battery systems effectively minimized grid imports during high-tariff hours, optimized load matching, and stabilized the microgrid's energy flow under varying seasonal conditions.

The findings confirm that renewable-integrated hybrid microgrids can provide technically reliable, economically viable, and environmentally sustainable solutions for electric mobility infrastructures in academic environments. Furthermore, the study highlights the strategic potential of energy storage and smart control systems in achieving decarbonized, cost-efficient, and resilient campus-scale EV charging networks.

Keywords: Renewable Energy-Based Microgrid, Electric Vehicle Charging Systems, Optimization, Techno-Economic Analysis, HOMER Grid.

Introduction

The 20th century witnessed the dominance of internal combustion engine (ICE) vehicles, powered by carbon-based fuels that revolutionized global transportation and mobility (Leach et al., 2020). However, this rapid industrial and automotive expansion has also intensified environmental degradation, contributing to air pollution and climate change (Towoju & Ishola, 2020). As the negative ecological impact of fossil fuel consumption became increasingly apparent, the global energy transition toward cleaner technologies gained unprecedented momentum (Williams & Blyth, 2022). Advances in power electronics, energy storage, and smart control systems have accelerated the adoption of electric vehicles (EVs), which provide an environmentally friendly and energy-efficient alternative to conventional automobiles. Electric mobility now extends across multiple scales, from personal vehicles and public transport fleets to micromobility applications such as e-bikes and scooters. While these technologies reduce emissions, their rapid proliferation has led to a significant rise in electricity demand worldwide (Hung & Lim, 2019).

Despite the transition toward electrification, global power generation remains predominantly reliant on fossil fuels, underscoring the need to integrate renewable energy sources into power systems. In Türkiye, as of 2025, the total installed electricity capacity reached 121.4 GW, consisting of 26.6 % hydropower, 20.2 % natural gas, 18.1 % coal, 11.7 % wind, 19.9 % solar, 1.4 % geothermal, and 2.1 % other sources (Enerji ve Tabii Kaynaklar Bakanlığı, 2025). This composition demonstrates remarkable progress in renewable energy expansion, particularly in the solar and wind sectors, but it also reveals continued dependence on carbon-intensive resources. Enhancing the share of renewables within national grids can play a crucial role in reducing import dependency, improving energy security, and achieving long-term decarbonization targets.

One of the most critical challenges in this transition is the synchronization between renewable generation and growing electricity consumption, particularly due to the widespread use of EVs. The limited charging infrastructure and intermittent nature of renewable sources create operational bottlenecks for both grid-connected and standalone systems. Battery storage technologies, though rapidly evolving, remain a key factor influencing the feasibility and economic performance of EV charging networks. Consequently, integrating EV charging infrastructure with hybrid renewable microgrids has become a promising strategy for sustainable energy management. Various studies have explored this approach in different contexts. Shafiq et al. (2023) assessed the techno-economic feasibility of renewable-powered EV charging stations in Pakistan, revealing significant cost reductions and improved grid stability. Sood et al. (2022) analyzed photovoltaic-based charging systems for workplaces and residential areas, identifying optimal configurations that minimize operational costs. Solanki et al. (2023) designed hybrid systems combining solar PV and energy storage, capable of exchanging surplus energy with the main grid. Similarly, Oladigbolu et al. (2023) conducted a technical and economic evaluation of autonomous renewable-based charging systems, demonstrating their cost-effectiveness and environmental advantages over traditional grid-dependent designs.

Expanding upon these findings, this study focuses on the design and techno-economic optimization of renewable-based hybrid microgrid configurations for multiple electric vehicle charging scenarios within a university campus environment, using the HOMER Grid optimization platform. The modeling framework considers five distinct charging cases—Highway Charger (Level 3, On-Demand), Multifamily Residential Charger (Level 2, On-Demand), Office Charger (Level 2, Deferrable), On-Demand Public Charger, and Overnight Fleet Charger (Level 3, Deferrable)—each simulated under nine different configuration scenarios (S1–S9). These configurations incorporate various combinations of solar PV, wind turbines, diesel generators, batteries, and grid connection.

This investigation aims to provide a comprehensive framework for analyzing how renewable-integrated microgrids can efficiently meet EV charging demands in academic and institutional environments. The outcomes of this research are expected to contribute to future planning strategies for sustainable campus energy systems and to serve as a reference for broader renewable-based EV charging infrastructure development.

Materials and Methods

The load profile of the hybrid microgrid system was developed using the 2024 operational data corresponding to the central campus of Yalova University. The primary load represents the aggregate electricity demand of academic and administrative buildings, laboratories, and auxiliary facilities throughout the year. According to the simulation results generated in HOMER Grid, the campus exhibits an average daily electrical demand of 1197.8 kWh/day, with an average load of 49.91 kW and a peak load of 172.5 kW, as illustrated in Figure 2. The load factor, calculated as 0.29, indicates a moderately fluctuating demand pattern, reflecting variations in daily occupancy, seasonal activities, and operational schedules of university buildings. The maximum peak load occurs in December, corresponding to the winter period when heating and lighting demands are at their highest levels.

In addition to the campus load, the system incorporates the energy requirements of electric vehicle charging stations (EVCSs), designed to simulate multiple charging scenarios under hybrid renewable microgrid configurations. The integration of EVCS loads with the campus demand profile allows a holistic evaluation of energy supply–demand balance and renewable utilization performance (Güven et al., 2024; Güven, 2025).

Climatic parameters—including ambient temperature, solar irradiance, and wind speed—were obtained from the Turkish State Meteorological Service (MGM) for the Yalova region. These datasets were processed to represent hourly values consistent with the simulation time step in HOMER Grid. Solar radiation data were applied to determine photovoltaic (PV) generation potential, while wind speed data supported the sizing and performance assessment of small-scale wind turbines. The correlation of climatic data with the load pattern ensures realistic modeling accuracy and enhances the reliability of techno-economic results under varying meteorological conditions.

Photovoltaic Panel

The PV system converts solar radiation into direct current (DC) electricity through semiconductor cells, typically made of silicon. PV panels are sustainable, low-emission energy sources widely used in residential and industrial applications. The output power of the PV module is defined by Eq. (1), which considers solar irradiance, temperature coefficient, and operating temperature to estimate the real-time power generation (Güven and Hatipoğlu, 2022).

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right) [1 + \alpha_f \ (T_C - T_{C,STC})]$$

The solar generation system uses Peimar SG300MBF modules with a rated capacity of 1 kW and 19.1% efficiency. The panels operate at 25 °C, have a temperature coefficient of –0.4 %/°C, and a derating factor of 80%. The estimated lifetime is 30 years, with a capital and replacement cost of 700 $/kW and an annual O&M cost of 70 $/year.

Diesel Jenerator

The diesel generator (DG) provides backup power when renewable sources are insufficient. Fuel consumption is modeled linearly with respect to generator output power, as shown in Eq. (2) (Güven, 2025). Emission factors for CO_2, NO_x, HC, and PM are based on standard diesel combustion data. Although DGs offer operational flexibility, their fuel dependency increases environmental impacts compared to renewable alternatives (Güven and Mete, 2021).

$$F_{DG} = a_1 P_{DG} + a_0 \ P_{DGR} \tag{2}$$

A diesel generator with an autosized capacity up to 1000 kW serves as a backup power source. It operates at a minimum load ratio of 25% with a fuel curve slope of 0.236 L/hr/kW. The emission factor is 16.5 g/L, lifetime 15,000 hours, and capital plus replacement costs are 1000 $/kW, with an O&M cost of 0.01 $/hour.

Wind Turbine

Wind turbines convert the kinetic energy of wind into mechanical and subsequently electrical energy. The turbine’s electrical power output depends on air density, swept area, and wind speed, as defined in Eq. (3). The model used in this study assumes an average hub height and efficiency consistent with small-scale distributed generation applications (Güven and Poyraz, 2021). Wind energy complements solar power, enhancing system reliability during periods of low solar radiation.

$$P = \frac{1}{2} p C_p A v_\omega^3 \tag{3}$$

A 4.2 kW AWS HC Wind turbine is integrated into the system. The turbine is installed at a 12 m hub height, with a 20-year lifespan. Both the installation and replacement costs are 7000 $/kW, and the annual O&M cost is 20 $/year. It supports the PV system by generating power during low solar radiation periods.

Battery Storage System

The battery bank stores excess renewable energy and supplies power during shortages (Güven, 2024a). The instantaneous output power is defined in Eq. (4), which accounts for internal resistance and nominal voltage:

$$P_{out} = I\,V_{output} = V_0 I - R_0 I^2 \tag{4}$$

The state of charge (SOC) variation follows Eq. (5), ensuring accurate modeling of charging–discharging behavior (Güven and Yücel, 2023):

$$SOC\quad(t + \Delta t) = min\{SOC(t)(1 - \delta) + \eta_{ch}(P_{gen} - P_L)\Delta t, SOC_{max}\} \tag{5}$$

The combined power generation from renewable and backup systems is expressed in Eq. (6):

$$P_{gen} = \begin{cases} \eta_{Inv} P_{PV} & PV\ Only \\ \eta_{Inv} P_{PV} + P_{DG} & PV\ and\ DG\ system. \end{cases} \tag{6}$$

During the charging process, the allowable charging power of the battery is limited by the maximum charging current, as represented in Eq. (7) (Güven and Yücel, 2025):

$$P_{gen} - P_L < P_{bat,c}^{lim} = I_{bat,c}^{lim} \times V_{bat} \tag{7}$$

The EnerStore 50 Agile Flow Battery provides 50 kWh nominal capacity (570 Ah, 100 V) with a round-trip efficiency of 72%. It operates between 10–100% state of charge and is designed for 30 years of service life. The capital cost is 780 $/unit, replacement 720 $/unit, and annual O&M cost is negligible.

Converter (Inverter/Rectifier)

The bidirectional converter ensures energy conversion between DC and AC buses (Güven, 2017). Its capacity is determined by Eq. (8), considering the peak load and DC/AC efficiency ratio:

$$P_{inv} = \frac{E_{L,max}}{\eta_{DC/AC}} \tag{8}$$

The System Converter operates at 1 kW rated capacity, with 95% inverter and rectifier efficiencies. The lifetime is 15 years, capital cost 600 $/kW, replacement 550 $/kW, and annual O&M 30 $/year. It ensures bidirectional DC-AC conversion between PV, storage, and the grid.

Grid Structure

The grid connection limit is 999.99 kW. Electricity tariffs are 0.40 $/kWh (06:00–17:00), 0.35 $/kWh (17:00–22:00), and 0.30 $/kWh (22:00–06:00), with an export tariff of 0.15 $/kWh valid throughout the year. The tariff model follows the Turkey national code for 2024.

Economic Parameters

Economic assumptions include a 20% discount rate, 17% inflation rate, and a 25-year project lifetime. These parameters were aligned with current national macroeconomic indicators to ensure realistic financial evaluation within HOMER Grid simulations (Güven, 2023).

Electric Vehicle Charging Stations

Electric vehicle (EV) charging stations represent a critical element of sustainable transportation infrastructure, supplying electricity to vehicle batteries and ensuring operational readiness (Güven, 2024b). These systems are categorized into alternating current (AC) and direct current (DC) technologies. While AC chargers operate at lower power levels and are generally suited for residential or workplace use, DC chargers enable rapid charging with higher output power, making them ideal for highway or fleet applications. Both types support multiple EV models through standardized connector interfaces and communication protocols (Güven, 2025).

Five EV charging station configurations were modeled within the campus microgrid using HOMER Grid v1.11.14, covering various power levels and user behaviors. Table 1 summarizes their key technical specifications, while Table 2 presents EV type distributions and charging characteristics at each station. The integration of these stations within the renewable-based microgrid enables simultaneous evaluation of on-demand and deferrable charging patterns under realistic operational conditions (Güven, 2024c).

Table 1. Technical characteristics of EV charging stations

Station Type	Charger Output Power (kW)	Number of Chargers	Average Sessions/day	Average Daily Load (kWh/day)	Charging Mode
Highway Charger (Level 3, On-Demand)	150	2	20	528	DC Fast
Multifamily Residential Charger (Level 2, On-Demand)	12	2	5	172	AC
Office Charger (Level 2, Deferrable)	12	2	10	85	AC
On-Demand Campus EV Charger	22	2	7	93	DC Fast
Overnight Fleet Charger (Level 3, Deferrable)	200	2	15	318	DC Fast

Table 2. EV type distribution and charging parameters

Station Type	EV Type	Proportion of EV Population (%)	Max Charging Power per EV (kW)	Average Charging Duration (min) / Energy (kWh)
Highway Charger (Level 3, On-Demand)	Large EVs / Small EVs	30 / 70	150 / 50	20 / 20 min
Multifamily Residential Charger (Level 2, On-Demand)	SUV EV / Small EV	30 / 70	150 / 50	260 / 260 min
Office Charger (Level 2, Deferrable)	Leaf / Model X / Model 3 / BMW i3	20 / 30 / 30 / 10	6.6 / 17.2 / 17.2 / 7.7	15–40 kWh
On-Demand Campus EV Charger	Hyundai Ioniq 5 / BYD Atto 3	30 / 20	220 / 80	35 / 40 min
Overnight Fleet Charger (Level 3, Deferrable)	Semitruck / Truck / Sprinter	10 / 30 / 60	200 / 50 / 50	500 / 80 / 120 kWh

System Integration

Figure 2 illustrates the Scenario-2 (S2) microgrid structure, which achieved the best techno-economic performance among the simulated configurations. It integrates PV panels, a battery storage system, the utility grid, and five distinct EV charging stations connected through a bidirectional converter. Both AC and DC buses are included to ensure energy balance between generation and demand sides.

Findings and Discussion

The simulation results for Scenario S2 demonstrate the techno-economic feasibility of integrating solar- and wind-based distributed generation with battery storage to supply different EV charging stations on the Yalova University campus. Monthly data revealed that electricity consumption and corresponding energy charges exhibited consistent seasonal variations across all station types, peaking during the summer months due to higher renewable generation and increased transportation activity. The Highway Fast-Charging Station (Level 3) showed the largest monthly energy demand, averaging approximately 400 kWh/day, whereas the Multifamily Residential and Office Chargers (Level 2) maintained more stable but lower consumption levels.

As presented in Table 3, monthly electricity consumption and energy charges varied significantly throughout the year across all EV charging stations. The highest total energy consumption occurred between May and August, corresponding to increased solar irradiance and elevated vehicle utilization. The Highway Charger (Level 3) recorded the largest monthly load, exceeding 400 kWh/day, while the Multifamily Residential and Office Chargers (Level 2) exhibited more stable and lower demand patterns ranging between 60–130 kWh/day. These variations highlight the influence of charger type, user behavior, and demand timing on overall system load.

The energy charge trend closely followed the consumption pattern, peaking in July (~65,000 $) and reaching its minimum in December (~20,000 $). This reflects a direct dependency between operational costs, renewable generation potential, and seasonal usage intensity. Conversely, smaller on-demand and residential chargers displayed moderate monthly energy fluctuations, confirming their suitability for distributed, lower-capacity microgrid integration. Overall, the data presented in Table 3 confirm that seasonal load management and renewable alignment are essential for optimizing both technical and economic performance in EV charging microgrids.

From Table 4, Scenario S2 demonstrated the most balanced performance among all configurations in terms of cost, efficiency, and environmental indicators. The Highway Charger (Level 3) achieved the highest annual savings (≈ 94,664 $/yr) with a payback time of 7.3 years, emphasizing the economic advantages of renewable-based high-capacity systems. The Multifamily Residential and Office Chargers yielded moderate returns with simple payback periods of 4.7 and 5.2 years, respectively, while maintaining relatively low CO_2 emissions (≈ 546–618 t/yr). Similarly, the On-Demand Charger exhibited comparable financial outcomes, validating the scalability of solar-dominant hybrid architectures for mid-range charging applications.

In contrast, the Overnight Fleet Charger (Level 3, Deferrable)—designed for large, flexible loads—had the highest CAPEX (5.32 M $) and energy charges but achieved the lowest fuel consumption (355 L/yr) and stable CO_2 emissions (≈ 2,908 t/yr). These outcomes highlight that large-scale hybrid renewable–grid integration can substantially reduce fossil-fuel dependence compared with generator-intensive configurations.

Overall, Scenario S2 achieved a favorable trade-off between investment cost, operational efficiency, and environmental performance. The integration of PV, wind, and battery storage systems significantly reduced grid dependency while improving the sustainability of EV charging infrastructure on campus. The findings confirm that renewable-assisted microgrids represent a practical and scalable solution for future electrified transportation networks in both university and urban environments.

Table 3. Monthly Energy and Economic Results (Scenario S2 for All EV Charging Stations)

Station	Month	Energy Charges ($)	Consumption (kWh)	Sales (kWh)	Monthly Total ($)
Highway Charger (Level 3, On-Demand)	January	27.078	-	180.522	27.018
	February	29.78	-	198.537	29.72
	March	43.982	-	293.212	43.922
	April	49.719	-	331.462	49.659
	May	60.325	-	402.169	60.265
	June	62.67	-	417.802	62.61
	July	65.306	-	435.376	65.246
	August	60.29	-	401.933	60.23
	September	54.685	-	364.564	54.625
	October	41.61	-	277.397	41.55
	November	26.229	-	174.86	26.169
	December	20.02	-	133.468	19.96
Multifamily Residential Charger (Level	January	4.37	77	29.311	4.298
	February	6.306	27	42.106	6.219
	March	10.265	-	68.433	10.205

2, On-Demand)	April	13.482	-	89.879	13.422
	May	16.447	-	109.645	16.387
	June	17.547	-	116.979	17.487
	July	17.581	-	117.206	17.521
	August	15.572	-	103.815	15.512
	September	14.561	-	97.071	14.501
	October	9.872	-	65.814	9.812
	November	5.033	-	33.554	4.973
	December	1.94	24	12.993	1.878
Office Charger (Level 2, Deferrable)	January	5.326	89	35.717	5.249
	February	7.375	13	49.198	7.3
	March	11.702	1	78.016	11.635
	April	15.002	-	100.014	14.942
	May	18.134	-	120.895	18.074
	June	19.207	-	128.048	19.147
	July	19.337	-	128.916	19.277
	August	17.194	1	114.625	17.13
	September	16.171	-	107.809	16.111
	October	11.174	3	74.5	11.11
	November	5.725	575	39.509	5.6
	December	2.295	1005	17.662	2.152
On-Demand EV Charger	January	4.814	48	32.206	4.746
	February	6.832	-	45.55	6.772
	March	10.946	-	72.971	10.886
	April	14.244	-	94.961	14.184
	May	17.188	-	114.59	17.128
	June	18.229	-	121.524	18.169
	July	18.339	-	122.261	18.279
	August	16.231	-	108.206	16.171
	September	15.339	-	102.263	15.279
	October	10.489	-	69.924	10.429
	November	5.382	-	35.88	5.322
	December	1.891	898	14.725	1.768
Overnight Fleet Charger (Level 3, Deferrable)	January	35.836	3	238.911	35.762
	February	38.711	-	258.075	38.651
	March	56.308	3	375.396	56.229
	April	62.394	2	415.966	62.322
	May	75.618	2	504.121	75.546
	June	78.377	3	522.518	78.291
	July	81.917	2	546.114	81.844
	August	75.972	3	506.483	75.902
	September	69.048	2	460.324	68.974
	October	53.822	3	358.817	53.749
	November	34.855	10	232.387	34.765
	December	27.58	59	184.001	27.493

Table 4. Techno-Economic and Environmental Results for EV Charging Scenarios (S2 Only)

Parameter	CASE-1: Highway Charger (Level 3, On-Demand)	CASE-2: Multifamily Residential Charger (Level 2, On-Demand)	CASE-3: Office Charger (Level 2, Deferrable)	CASE-4: On-Demand EV Charger	CASE-5: Overnight Fleet Charger (Level 3, Deferrable)	Unit
CAPEX	4,409,940	1,556,874	1,629,792	1,598,222	5,316,340	$
OPEX	258,085	33,535	36,716	33,551	317,384	$/yr
Annual Total Savings	94,664	60,205	56,607	59,851	95,633	$/yr
Annual Utility Bill Savings	82,304	59,986	54,239	57,908	79,074	$/yr
Annual Demand Charges	0	42	186	71	189	$/yr
Annual Energy Charges	540,975	132,256	147,966	139,205	689,716	$/yr
Discounted Payback Time	7.3	5.1	5.6	5.7	8.9	yr
Simple Payback Time	6.6	4.7	5.2	5.3	7.9	yr
LCOE	0.007	0.048	0.041	0.044	0.000	$/kWh
IRR	15.11	21.29	19.36	19.00	12.62	%
Net Present Cost	310,427	943,523	958,250	984,565	488,620	$
CO_2 Emissions	2,278.6	546.1	617.7	579.2	2,908.2	ton/yr
Annual Fuel Consumption	1,420	5,457	3,868	4,281	355	L/yr

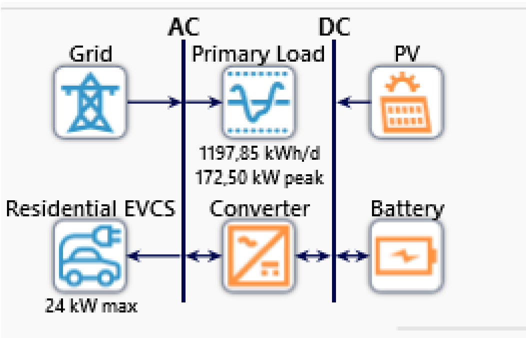

Figure 1. Microgrid configuration for residential EV charging application.

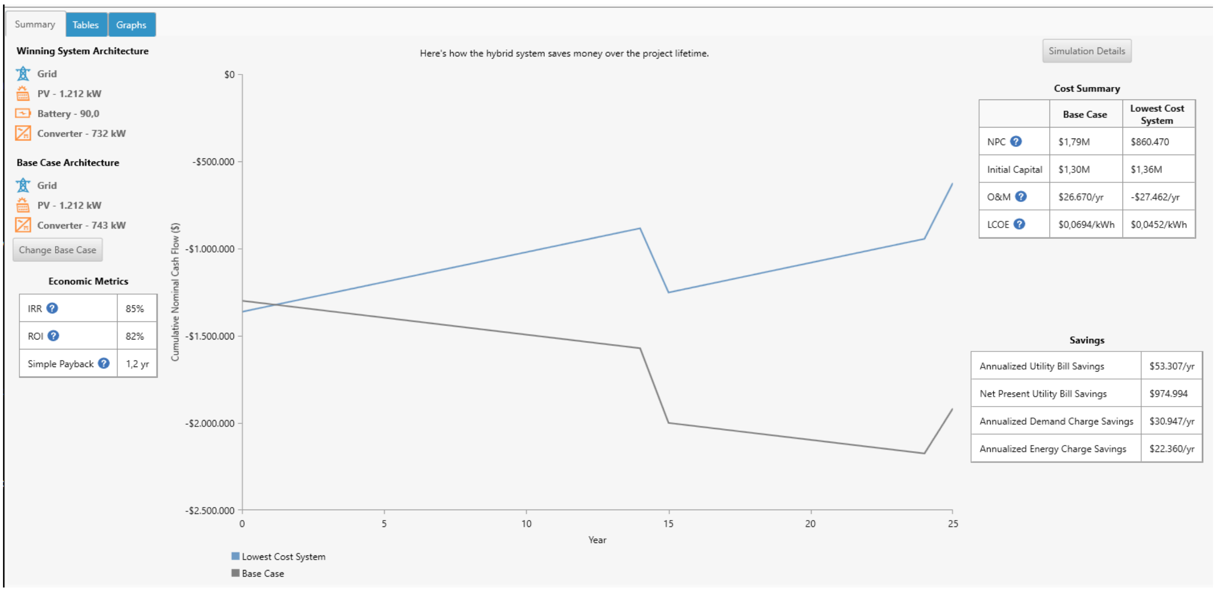

Figure 2. Comparative economic performance of the base and optimized hybrid systems over the project lifetime.

Figure 2 compares the economic performance of the optimized hybrid microgrid and the base grid-connected configuration throughout the 25-year project lifetime. The optimized system, incorporating PV (1.21 kW), battery storage (90 units), and a 732 kW converter, achieved a net present cost (NPC) of 860,470 $, representing nearly a 52% reduction compared to the base case (1.79 M $). Similarly, the levelized cost of energy (LCOE) decreased from 0.0694 $/kWh to 0.0452 $/kWh, demonstrating the cost efficiency of the hybrid design. The internal rate of return (IRR) of 85% and simple payback period of 1.2 years confirm the strong financial viability of the system. Overall, the hybrid configuration provides substantial savings—53,307 $/yr in utility bills and 30,947 $/yr in demand charges—highlighting its effectiveness in reducing lifetime operating expenses and enhancing economic sustainability.

Figure 2 presents the annual energy balance and monthly electricity production profile of the grid-connected hybrid microgrid configuration. The system consists of a 1.21 kW Peimar SG300MBF PV array, a 90-string EnerStore 50 Agile Flow Battery, and a 732 kW converter. Annual PV generation reached 1,586,457 kWh, accounting for 99% of total production, while grid imports contributed only 14,341 kWh (0.9%), demonstrating the system's high renewable fraction of 99%. On the demand side, AC primary load consumed 437,215 kWh (31.5%), EV charging utilized 62,660 kWh (4.5%), and grid sales accounted for 887,261 kWh (64%), indicating substantial excess energy fed back to the grid. The excess electricity exported annually totaled 68,591 kWh, resulting in a maximum renewable penetration of 87.83%.

Seasonal analysis shows that PV output peaks between May and August, corresponding to higher solar irradiance levels, while production declines during winter months (November–January). This generation pattern closely aligns with regional solar potential and supports stable operation of the microgrid under varying load conditions. Overall, the results highlight the strong self-sufficiency and renewable integration capacity of the designed system.

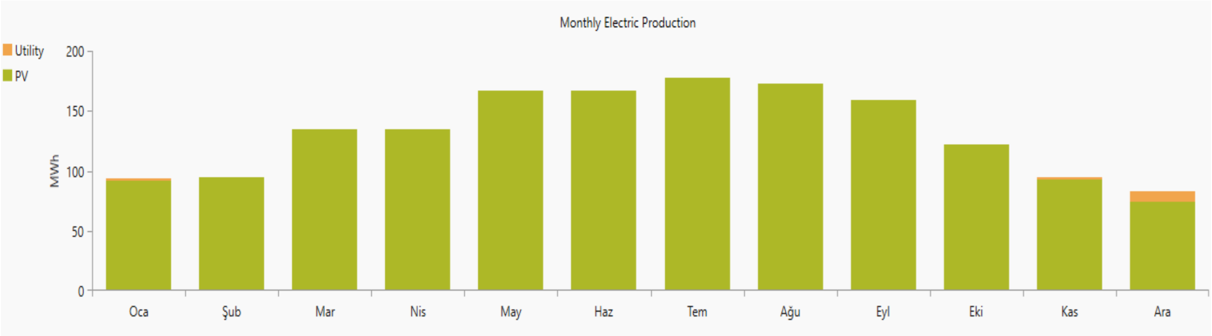

Figure 3. Monthly electricity production profile of the PV–battery–grid hybrid system

Figure 3 illustrates the monthly electricity generation profile of the hybrid renewable system integrating PV panels, battery storage, and the utility grid. Solar energy dominates the total production throughout the year, contributing over 99% of the total generation. The system achieves its highest monthly outputs between May and August, corresponding to peak solar irradiance and extended daylight duration. Conversely, generation declines during November to January, when sunlight availability is minimal. The minor contribution of utility power during these months demonstrates the system's ability to maintain stable operation and self-sufficiency, even under reduced PV output. This pattern highlights the reliability of the hybrid configuration in balancing renewable variability and sustaining consistent power delivery for EV charging applications.

Figure 4 presents the annual charging load profile and energy distribution for the Multifamily Residential Charger (Level 2, On-Demand). The system recorded 1,226 charging sessions per year, delivering approximately 62,660 kWh of electricity to EVs. Each session provided an average of 5.1 kWh, with a peak charging power of 24 kW and a utilization factor of 29.8%, indicating moderate yet consistent charger use throughout the year. The color-intensity variation across the 24-hour axis highlights dynamic charging activity, concentrated mainly during evening hours when residential energy demand typically peaks. The minimal missed session rate (1.6 per day) confirms the system's adequacy in meeting user requirements and its operational stability under on-demand conditions. Overall, the load distribution pattern demonstrates efficient integration of the residential EV charger within the hybrid microgrid, supporting balanced energy management and reliable service provision across all seasons.

	Sessions per Year	Annual Energy Served (kWh)	Energy per Session (kWh)	Sessions per Day	Peak Power (kW)	Missed sessions per Day (avg.)	Utilization Factor (%)
Multifamily Residential Charger (Level 2, On-Demand)	1226	62,660	51.1	3.4	24.0	1.6	29.8

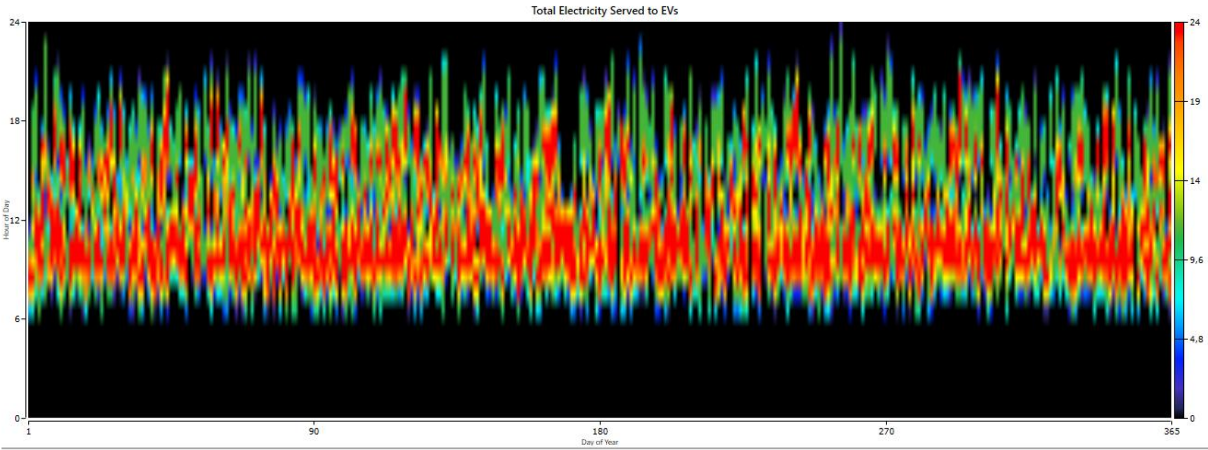

Figure 4. Annual charging behavior and electricity served by the Multifamily Residential Charger (Level 2, On-Demand)

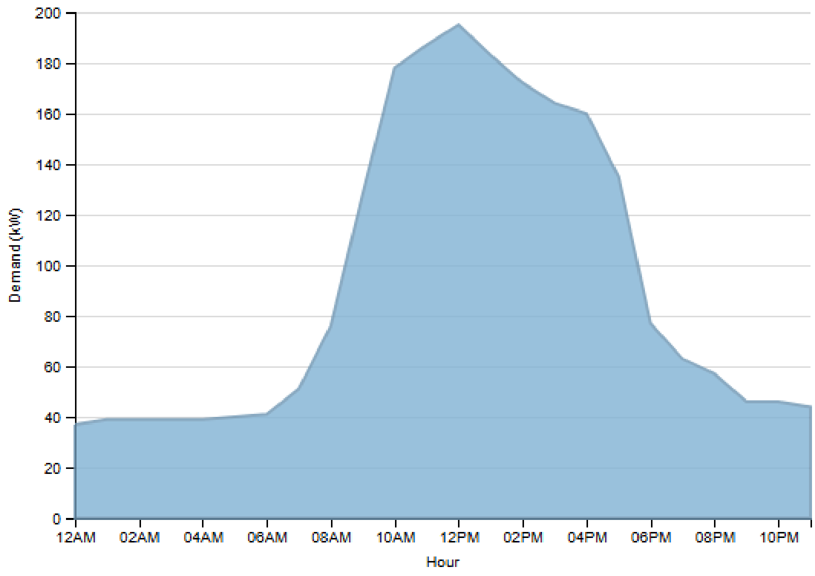

Figure 5. Daily load profile on the peak demand day (December 18)

Figure 5 illustrates the hourly load variation for the day with the highest total electricity demand, observed on December 18. The load remains stable during nighttime hours (00:00–06:00) at around 35–40 kW, reflecting baseline residential and auxiliary system consumption. A sharp increase begins after 08:00 AM, reaching a peak demand of approximately 195 kW at noon, primarily driven by the combined operation of EV chargers and building loads. The demand gradually decreases after 04:00 PM, stabilizing near 40 kW during evening hours. This pattern reflects typical diurnal consumption behavior, where high solar generation and daytime user activity significantly influence the total demand curve. The observed peak period aligns with solar production hours, highlighting the importance of coordinated energy management between renewable generation, storage systems, and EV charging demand to ensure optimal grid performance and reliability.

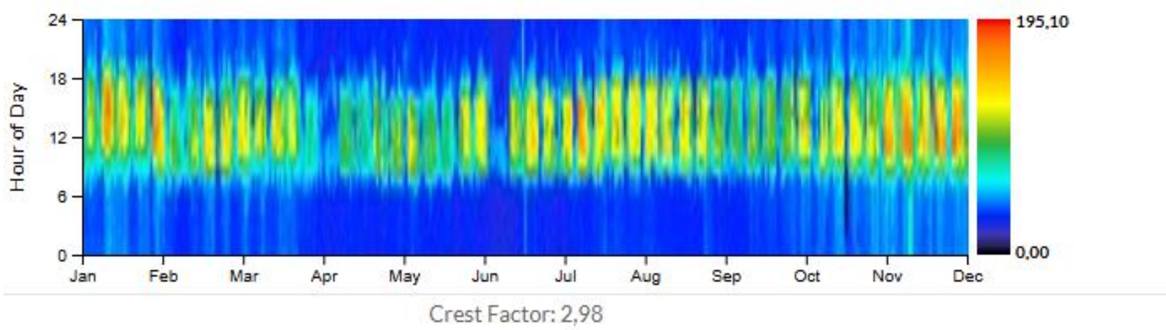

Figure 6. Annual heat map showing hourly energy consumption patterns of the microgrid system

Figure 6 presents the annual heat map illustrating hourly variations in electricity consumption throughout the year. The color gradient—from blue (low) to red (high)—represents the magnitude of power demand, with the maximum value reaching approximately 195 kW. The load profile indicates a distinct diurnal pattern, where energy use intensifies between 08:00 AM and 08:00 PM, coinciding with daytime operational and charging activities. Seasonal fluctuations are also visible: higher demand is observed during spring and summer months (April–August) due to extended daylight and increased EV charging sessions, while winter months exhibit comparatively lower yet stable consumption levels. The calculated crest factor of 2.98 highlights moderate variability in the load curve, signifying efficient demand distribution and effective load management across the year. Overall, the heat map confirms that the hybrid microgrid system maintains consistent energy delivery and demand balance under varying operational conditions.

Figure 7 illustrates the comparative analysis of utility bill structures for the hybrid configuration (Solar + Storage: Battery + Grid) and the base case relying solely on grid power. The hybrid system demonstrates a substantial reduction in total utility expenses, primarily due to lower energy consumption charges, while maintaining minimal demand costs. In contrast, the base case scenario exhibits significantly higher overall costs driven by grid dependency and peak load contributions. The observed shift in the cost distribution highlights the economic advantage of integrating PV generation and battery storage, which effectively reduces grid imports during high-tariff hours. These results confirm that hybridization not only improves energy autonomy but also delivers long-term financial benefits through reduced operational expenditure and stabilized demand-side performance across the project lifetime.

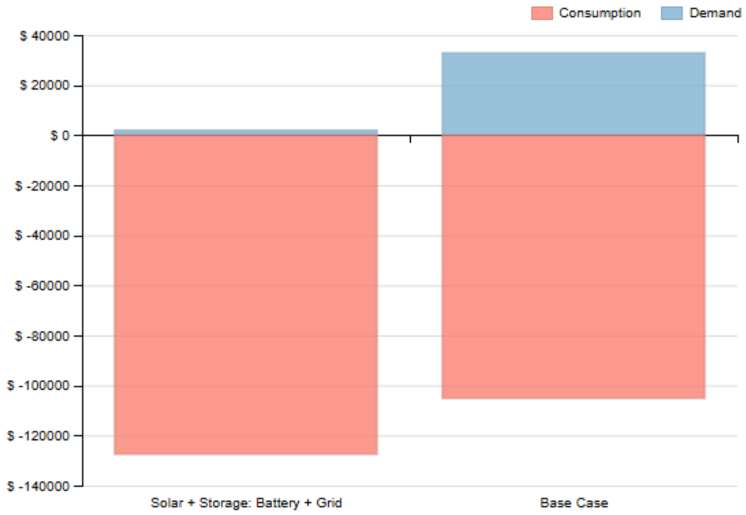

Figure 7. Comparison of utility bill components between the hybrid and base case systems

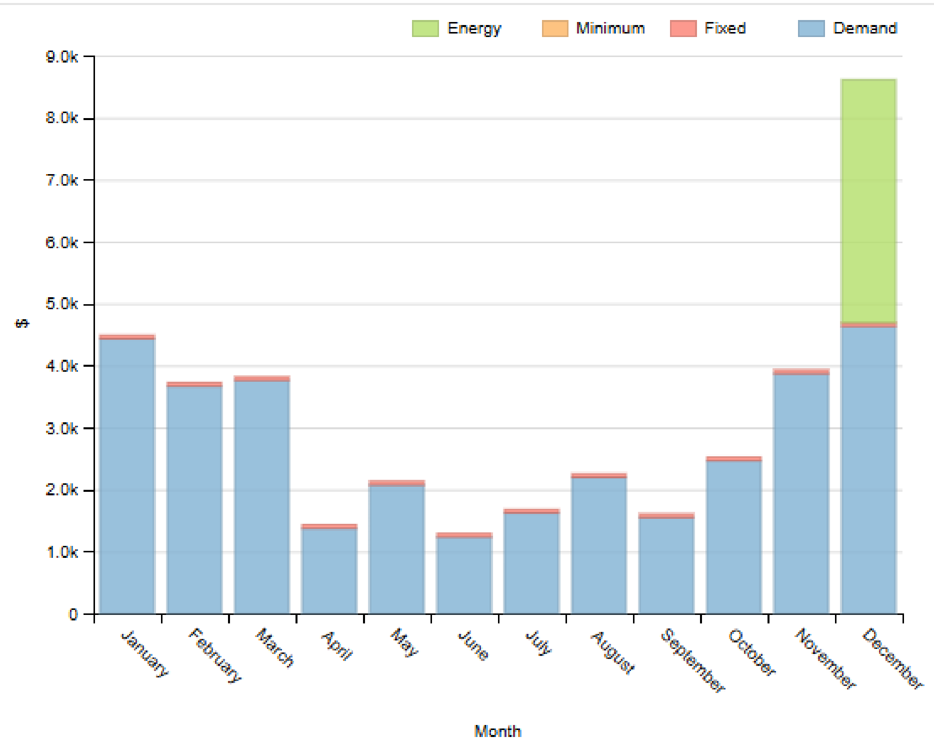

Figure 8. Monthly breakdown of electricity bill components for the hybrid system

Figure 8 illustrates the monthly distribution of electricity bill components—including energy, demand, fixed, and minimum charges—for the hybrid (Solar + Storage + Grid) configuration. The results show that demand-related costs dominate the total monthly expenses, particularly in winter months (January, November, and December), when solar generation is limited, and grid dependency increases. Conversely, during spring and summer months (April–September), both demand and energy charges decrease significantly due to enhanced PV output and partial battery discharge coverage. The substantial rise in energy costs during December corresponds to higher consumption under reduced renewable availability. This monthly fluctuation pattern highlights the impact of seasonal generation profiles and load behavior on the financial performance of the system. Overall, the hybrid structure maintains a balanced cost distribution by leveraging renewable production and storage, effectively minimizing high-tariff grid imports during peak hours and optimizing annual utility expenditures.

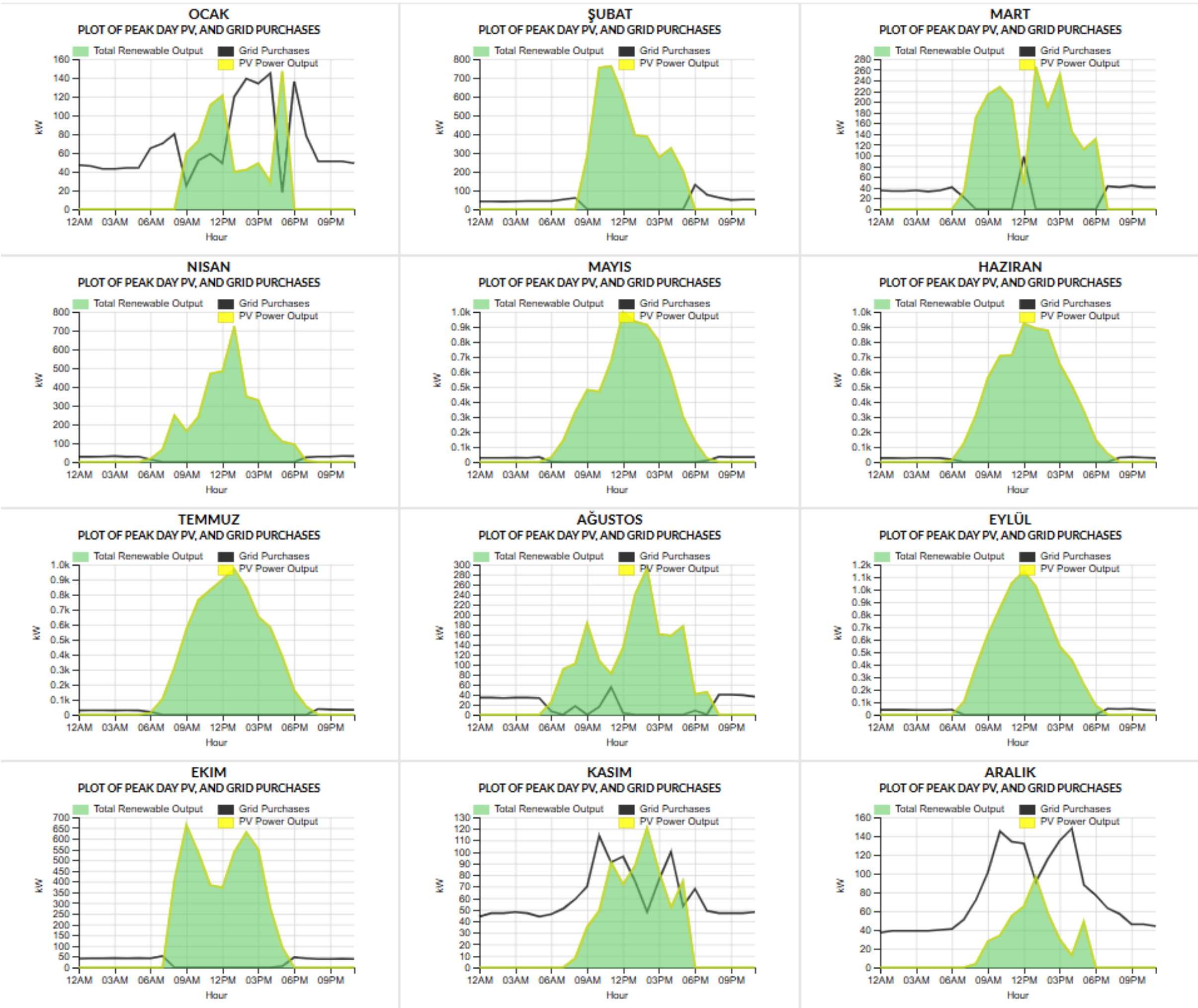

Figure 9. Monthly variation of PV generation, total renewable output, and grid purchases during peak demand days

Figure 9 illustrates the hourly distribution of PV generation, total renewable energy output, and grid electricity purchases for the peak demand days across each month of the year. The green-shaded regions represent PV power generation, while the black curves indicate the grid import profile. This comparative visualization provides valuable insight into the temporal alignment between renewable energy availability and system demand behavior.

From January to March, renewable generation remains relatively low, with limited solar irradiation and shorter daylight hours, resulting in significant grid dependency, particularly during early morning and evening hours. April through September marks a substantial increase in PV output, peaking between 11:00 AM and 2:00 PM, where solar irradiance intensity is highest. During these months, the renewable contribution nearly satisfies the load demand, demonstrating strong self-sufficiency and minimal grid import activity.

June, July, and August show the highest PV energy production—coinciding with longer daylight duration and enhanced solar efficiency—allowing the system to achieve nearly complete renewable coverage during midday. Grid purchases are consequently reduced to near zero during this interval. This indicates optimal utilization of the hybrid system's generation and storage resources.

In contrast, during October to December, declining solar availability causes a notable resurgence in grid dependency, particularly in the early morning and evening peaks, when PV output falls below 50 kW. The sharp drop in renewable output after sunset necessitates grid support, especially under higher load conditions typical of the winter season.

Overall, this monthly analysis confirms that the PV + battery + grid hybrid system effectively reduces grid reliance during solar-rich months while maintaining energy reliability throughout the year. The strong correlation between renewable peaks and daytime demand emphasizes the system's operational resilience and its capability to enhance load matching efficiency. Furthermore, this performance highlights the strategic importance of energy storage in stabilizing power supply and ensuring cost-effective, low-carbon operation of EV charging infrastructures within campus-based microgrids.

Conclusion and Recommendations

The techno-economic analysis demonstrated that integrating PV, wind, and battery storage systems within EV charging infrastructures offers a cost-effective and sustainable alternative to grid-dependent operation. Among the simulated configurations, Scenario S2 (Solar + Storage + Grid) achieved the most balanced performance, combining moderate investment costs with low operating expenses and minimal environmental impact. The system significantly reduced annual energy charges and CO_2 emissions while improving energy self-sufficiency through optimized renewable utilization and storage management.

The Highway Charger (Level 3) exhibited the highest annual savings, confirming the feasibility of renewable-powered fast-charging solutions for large-scale transportation hubs. Similarly, Multifamily Residential and Office Chargers (Level 2) achieved favorable payback periods of approximately 5 years, highlighting their economic viability for distributed urban installations. Across all cases, hybrid renewable–grid integration effectively mitigated fuel consumption and stabilized operational costs compared to conventional generator-based systems.

From an environmental standpoint, the deployment of renewable-dominant microgrids can significantly reduce carbon emissions and enhance local energy security on university campuses. These systems not only decrease dependency on fossil fuels but also provide a scalable model for sustainable EV infrastructure expansion in academic and urban contexts.

Recommendations for future work include:

- Expanding the system analysis to incorporate real-time dynamic load forecasting and vehicle-to-grid (V2G) integration to further improve flexibility and grid stability.
- Conducting sensitivity analyses on economic parameters such as inflation, discount rate, and electricity tariff structures to assess long-term investment risks.
- Exploring hybrid hydrogen–battery configurations for energy storage to achieve higher renewable penetration and improve resilience under seasonal variability.
- Extending the study to multi-campus or city-scale EV networks to evaluate scalability, interoperability, and policy implications for future smart-grid applications.

Overall, the results validate that renewable-based microgrids can serve as a technically robust and economically attractive pathway for sustainable electric mobility infrastructure in university environments.

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All simulations and evaluations were performed using the HOMER Grid software, and the results include findings on the optimization and techno-economic assessment of electric vehicle charging systems integrated into renewable energy–based microgrids on university campuses.

References

Güven, A. F. & Hatipoğlu, C. (2022). Şebekeden bağımsız güneş/rüzgâr/biyogaz/yakıt hücresi/batarya tabanlı hibrit enerji sisteminin tekno-ekonomik analizi: Muğla Zaferler Köyü vaka çalışması. EMO Bilimsel Dergi, 12(23), 53–65.

Güven, A. F. & Mete, M. K. (2021). Feasibility study and economic analysis of on-grid hybrid energy system for Balıkesir Province Erdek. Chamber of Mechanical Engineering, 63(706), 138–158. DOI: 10.46399/muhendismakina.1085748.

Güven, A. F. & Poyraz, E. (2021). Feasibility study and techno-economic analysis of stand-alone hybrid energy system for Muğla Province Köyceğiz. The Black Sea Journal of Sciences, 11(1), 70–85. DOI: 10.31466/kfbd.880437.

Güven, A. F. & Yücel, E. (2023). Application of HOMER in assessing and controlling renewable energy-based hybrid EV charging stations across major Turkish cities. International Journal of Energy Studies (TESPAM). DOI: 10.58559/ijes.1324236.

Güven, A. F. & Yücel, E. (2025). Sustainable energy integration and optimization in microgrids: Enhancing efficiency with electric vehicle charging solutions. Electrical Engineering, 107(2), 1541–1573. DOI: 10.1007/s00202-024-02619-x.

Güven, A. F. (2017). Bahçelievler Belediye Başkanlık Binasının enerji ihtiyacının güneş ve rüzgar sistemi ile karşılanması, optimizasyonu ve maliyet analizi. Sinop University Journal of Natural Sciences, 2(1), 24–36.

Güven, A. F. (2023). Dandelion-optimizer based power sharing in hybrid renewable energy system optimum sizing with EV: Grid-connected, wind, solar, battery, electric vehicles. 14th International Conference on Thermal Engineering: Theory and Application, 1–3.

Güven, A. F. (2024a). Cost-effective and sustainable off-grid hybrid energy systems: Optimizing hydrogen integration in microgrids using HOMER Pro. 4th International World Energy Conference, Kayseri, Türkiye.

Güven, A. F. (2024b). Design and optimization of renewable energy-based electric vehicle charging stations: A case study in Yalova. 4th Global Conference on Engineering Research, 21–36.

Güven, A. F. (2024c). Integrating electric vehicles into hybrid microgrids: A stochastic approach to future-ready renewable energy solutions and management. Energy, 303, 131968. DOI: 10.1016/j.energy.2024.131968.

Güven, A. F. (2025). A novel hybrid salp swarm Kepler optimization for optimal sizing and energy management of renewable microgrids with EV integration. Energy, 137696.

Güven, A. F., Mengi, O. Ö., Bajaj, M., Azar, A. T., & El-Shafai, W. (2025). Integrated techno-economic optimization and metaheuristic benchmarking of grid-connected hybrid renewable energy systems using real-world load and climate data. *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, *13*, 101099.

Güven, A. F., Türkmen, Ş., Aşıklı, E. & Örnek, G. (2023). Investigating the effects of different types of battery impacts in energy storage systems on standalone hybrid renewable energy systems. The Black Sea Journal of Sciences, 13(3), 943–964. DOI: 10.31466/kfbd.1275823.

Güven, A. F., Uzuner, N., Kaya, Y. & İbiş, S. (2024). Energy efficiency and emission impacts of hybrid energy systems for public buildings: Analyzing the role of boilers, natural gas, and gasoline generators. 4th International World Energy Conference, Kayseri, Türkiye.

Hung, N. B., & Lim, O. (2020). A review of history, development, design and research of electric bicycles. Applied Energy, 260(August 2019), 114323. doi: 10.1016/j.apenergy.2019.114323.

Leach, F., Kalghatgi, G., Stone, R., & Miles, P. (2020). The scope for improving the efficiency and environmental impact of internal combustion engines. Transportation Engineering, 1(April). doi: 10.1016/j.treng.2020.100005.

Oladigbolu, J. O., Mujeeb, A., Al-Turki, Y. A., & Rushdi, A. M. (2023). A Novel Doubly-Green Stand-Alone Electric Vehicle Charging Station in Saudi Arabia: An Overview and a Comprehensive Feasibility Study. IEEE Access, 11(April), 37283–37312. doi: 10.1109/ACCESS.2023.3266436.

Shafiq, A., Iqbal, S., Rehman, A. U., Elbarbary, Z. M. S., Kotb, H., Selim, A., & Kamel, S. (2023). Integration of solar based charging station in power distribution network and charging scheduling of EVs. Frontiers in Energy Research, 11(January), 1–15. doi: 10.3389/fenrg.2023.1086793.

Solanki, L., Vadhera, S., & Sandhu, K. S. (2023). 10.3-kW Solar PV Grid-Tied Charging of Li-Ion Batteries in Battery Swapping Stations for EVs Using HOMER Pro. Renewable Resources and Energy Management, 1-8. doi:10.1201/9781003361312.

Sood, S., Kumar, R., & Tiwari, N. K. (2022). Enviro-Economic Assessment of Energy Sources Used for Electric Vehicle Charging. 2022 1st International Conference on Sustainable Technology for Power and Energy Systems, STPES 2022, 1–5. doi: 10.1109/STPES54845.2022.10006604.

Towoju, O. A., & Ishola, F. A. (2020). A case for the internal combustion engine powered vehicle. Energy Reports, 6, 315–321. doi: 10.1016/j.egyr.2019.11.082.

Williams, I. D., & Blyth, M. (2023). Autogeddon or autoheaven: Environmental and social effects of the automotive industry from launch to present. Science of the Total Environment, 858(July 2022), 159987. doi: 10.1016/j.scitotenv.2022.159987.