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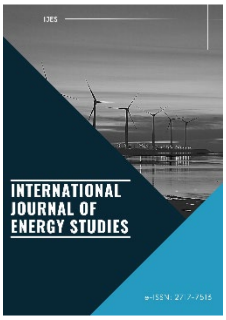

Research Article

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Design of a hybrid renewable energy system and green hydrogen production for smart cities: A carbon emission reduction approach

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Highlights

- Hybrid Renewable Energy System: Design and optimization of a hybrid renewable energy system (HRES) combining photovoltaic (PV) panels, wind turbines, biogas generators, and hydrogen production to meet the electricity and hydrogen needs of a city.
- Techno-Economic Analysis: Detailed evaluation of the system's techno-economic performance, including net present cost (NPC), levelized cost of electricity (LCOE), and renewable energy fraction.
- Sustainability Focus: The system meets 100% of electricity demand from renewable sources and reduces CO_2 emissions through hydrogen production and the use of hydrogen-powered vehicles.
- Optimization Results: Numerical analysis involving 14,550 simulations and 2,870 optimization cases, resulting in an optimized system with a 0.3959 $/kWh LCOE and 52.3 billion $ NPC.
- Practical Application: The proposed model is adaptable for other cities and demonstrates potential for expanding green hydrogen production.

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ABSTRACT

The rapid growth of population and industrial development worldwide has significantly increased energy demand. With the limitations and environmental impacts of conventional energy resources, renewable energy sources are essential for sustainable development. This study presents a renewable hybrid energy system designed to meet a city's electricity needs while generating green hydrogen for hydrogen-powered vehicles, a rising trend in transportation. The goal is to create a self-sufficient and environmentally friendly smart city. The proposed system integrates photovoltaic panels, wind turbines and a biomass generator, supported by lithium-ion batteries for energy storage and green hydrogen generation. Optimized through numerical analysis of experimental load data, the system is designed to handle an average annual electrical load of 14,946,686.40 kWh and produce 58.5 kg of hydrogen daily. A total of 14,550 simulations were conducted, yielding a levelized cost of electricity (LCOE) of $0.3959/kWh. The system is projected to reduce 9,398 tons of CO_2 emissions annually. Additionally, the use of 150 hydrogen-powered vehicles in the smart city is estimated to prevent further emissions of 325,215 tons/year, 295,650 tons/year, and 204,491 tons/year under different scenarios. This research highlights the transformative potential of hybrid renewable energy systems and hydrogen-powered vehicles for urban sustainability. By substantially reducing carbon emissions, it supports the development of greener, smarter cities and opens avenues for future innovations in renewable energy integration and sustainable urban planning.

Keywords: Green hydrogen, Hybrid renewable energy, Energy storage, Smart green city

1. INTRODUCTION

The global demand for electricity continues to rise rapidly, driven by population growth and industrialization. Currently, a significant portion of this demand is met through fossil fuels, which unfortunately contribute to severe environmental challenges such as increasing greenhouse gas emissions, global warming, and acid rain. These issues have necessitated a shift towards renewable energy sources such as solar, wind, tidal, and biomass, which have gained prominence in recent decades. Among these, solar and wind energy-both driven by the sun's indirect effects-are particularly vital. Biomass energy, supported by advancements in gasification technology, is also gaining popularity for electricity generation, especially in residential sectors, where it can contribute significantly to carbon peaking [1-4].

Recent global challenges, including wars, earthquakes, pandemics, and cyber-attacks, have prompted people to adopt more isolated lifestyles. These circumstances underscore the need for energy systems that can operate independently of centralized infrastructure. Self-sufficient energy systems that integrate generation, consumption, and storage processes offer sustainable and environmentally friendly solutions, particularly in scenarios where grid access is limited or non-existent.

The Paris Agreement, which aims to reduce global carbon emissions, has further emphasized the urgency of such solutions. Turkiye, a signatory to this agreement, has committed to achieving net-zero emissions by 2053. In this context, solar energy stands out as a particularly viable option, given Turkiye’s higher solar potential compared to many developed countries [5]. While the electricity sector is a primary contributor to greenhouse gas emissions, the transportation sector also plays a significant role. According to the Environmental Protection Agency (EPA), 28% of greenhouse gas emissions in the United States originate from transportation, while 25% come from electricity production [6]. Transitioning to hydrogen and electric vehicles is thus essential to mitigate emissions in the transportation sector.

A hybrid renewable energy system (HRES) integrates multiple renewable energy sources, providing a solution to the fluctuating and unpredictable characteristics of these resources [7]. Photovoltaic (PV) hybrid systems are often equipped with batteries to ensure uninterrupted power supply [8]. By integrating solar, wind, and biomass energy sources with various storage solutions, HRES can provide consistent and environmentally friendly energy.

Simulation and optimization tools like Homer pro are widely used in the design and analysis of HRES. Developed by the National Renewable Energy Laboratory (NREL) and later commercialized by Homer energy, this software evaluates the technical and economic feasibility of hybrid systems for applications ranging from off-grid villages to grid-connected campuses and military installations.

Numerous studies have utilized Homer pro to explore the potential of HRES in diverse contexts. For example, Ahmad et al. conducted a techno-economic analysis of a grid-connected hybrid PV-wind-biomass system for a rural area in Pakistan [9]. Aykut and Terzi evaluated the environmental and economic aspects of a university campus in Turkiye powered by PV, wind, and biomass [10]. Other researchers have optimized HRES for applications in Morocco [11], China [12], Pakistan [13], and Nigeria [-14], India [15-16] demonstrating the versatility of these systems across different geographic and operational contexts.

Beyond electricity generation, many studies have explored the integration of hydrogen production into HRES. For instance, Turkdogan designed a system to meet the electricity and hydrogen needs of a family [17], while Gokcek and Kale analyzed a hydrogen refueling station powered by a hybrid system in western Turkiye [18]. Other studies have focused on hydrogen production using floating PV [19] and hybrid configurations involving PV, wind, electrolyzers and fuel cells [20].

The novelty of this study lies in its dual focus. First, it addresses the electricity needs of an entire city using renewable resources, particularly in the context of crisis scenarios such as the 2023 Kahramanmaras earthquake. The proposed system is designed to be self-sufficient and independent of external energy sources, leveraging real-world electricity consumption data for enhanced accuracy. Second, it evaluates the potential for green hydrogen production in Kahramanmaras, a region in southeastern Turkiye, contributing to the academic discourse on hydrogen development in the country. In order to ensure realistic and applicable results, detailed annual consumption data reflecting experimental load profiles were incorporated into the modeling process by Homer pro demo version. These data sets provided a robust foundation for optimizing the proposed system, aligning numerical outcomes with practical usage patterns.

This paper distinguishes itself from the existing literature by addressing the energy needs of an entire city under crisis conditions, such as the aftermath of the 2023 Kahramanmaras earthquake, through a renewable hybrid energy system. Unlike previous studies, which often focus on smaller-scale applications such as residential buildings, villages, or specific industrial facilities, this research demonstrates the feasibility of a large-scale, self-sufficient energy system that integrates electricity generation, storage, and green hydrogen production. The use of real-world electricity consumption data ensures practical applicability and enhances the accuracy of the proposed model. Furthermore, the paper explores the dual functionality of the system by not only meeting urban energy demands but also providing sustainable hydrogen production for transportation, a critical step towards achieving net-zero emissions. This comprehensive approach contributes to the academic and practical advancements in renewable energy integration, particularly in regions like Turkiye with high solar energy potential and strategic importance for hydrogen economy development.

This study addresses a significant gap in the literature by designing a large-scale hybrid energy system, particularly suitable for crisis scenarios. Additionally, it aims to contribute to carbon neutrality in the transportation sector. The study differentiates itself from existing research in the following ways: unlike most studies that primarily focus on small-scale applications [9-21], such as villages, settlements, or individual facilities, this research adopts a comprehensive, city-scale approach. While renewable energy systems, electricity generation, and hydrogen production are typically studied separately in the existing literature, this study integrates both processes, enabling the simultaneous production of electricity and hydrogen. The use of real electricity consumption and meteorological data from Kahramanmaras enhances the accuracy and applicability of the obtained results. The methodology applied for determining electricity consumption can also be utilized for consumption analysis in other provinces.

The paper is organized as follows: the proposed system is introduced with details on the installation location, meteorological characteristics, and biomass availability. The load profiles, including electricity and hydrogen demands, are outlined next. This is followed by a description of the system components, their dimensions, and associated costs. The simulation results are then presented, along with a discussion of the system's environmental impacts. Finally, the paper concludes with key findings and suggestions for future research directions.

2. DESIGN AND COMPONENTS OF THE PROPOSED MODEL

The proposed system is developed to supply both the electricity demand of a city and the hydrogen needs of hydrogen-fueled vehicles for urban transportation, all while utilizing solely renewable energy sources. In order to realize the system, a hydrogen-integrated hybrid energy system has been developed, as illustrated in Fig. 1. The system consists of two primary loads: electricity and hydrogen. In the system, electricity is generated from three sources: biomass resource biogas generator, PV panels, and wind turbines. The electricity generated is used directly to power the electrical loads and additionally by the electrolyzer to produce hydrogen. In the event of excess electricity, it is stored in batteries. At some times, such as when there is little or no wind, when the sun is not shining (at night), or when there is little sunlight, generation may not be able to meet demand. In these cases, batteries provide energy to the system. The hydrogen fuel stored in the hydrogen tank is transferred to the vehicles and used to transport the cars for enough distance.

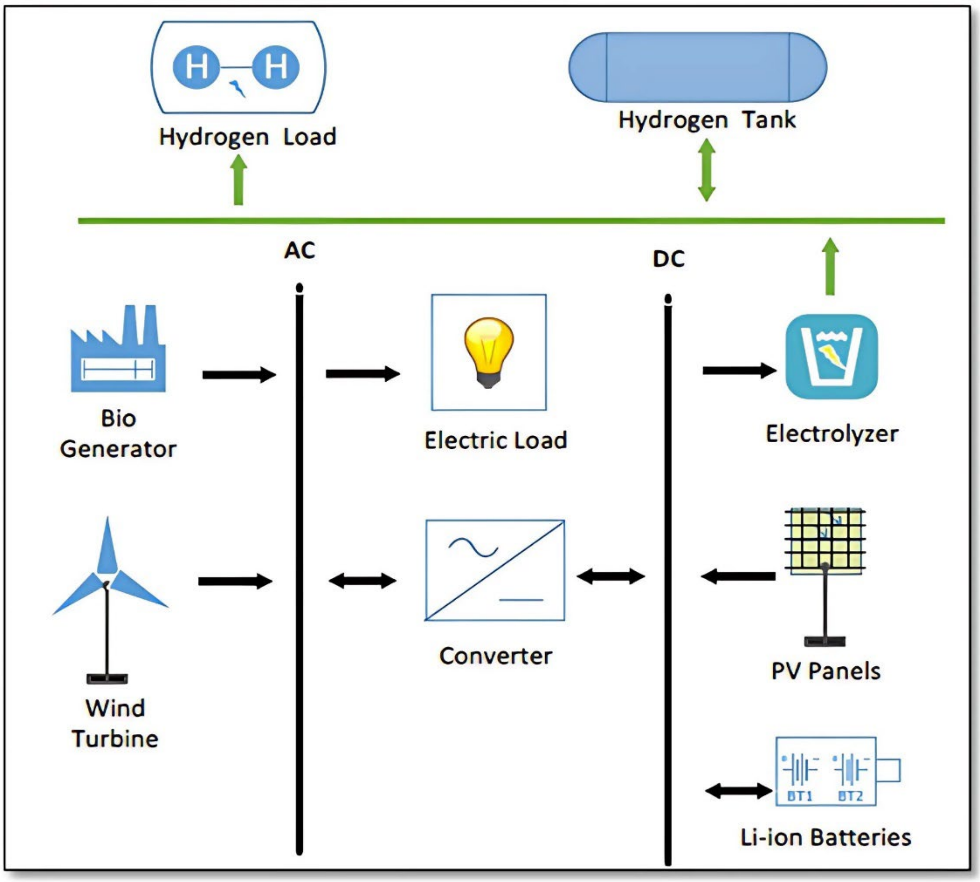


Figure 1. Schematic representation of the hydrogen-ıntegrated hybrid energy system model

Designed system consists of several steps. Firstly, the site where the system will be planned is determined in software and entered the meteorological information such as solar irradiation, temperature and wind speed for this selected location. In the second step the load demands of the system are determined. The next step is to select the components to be used in the system based on capital charge, replacement charge and operation & maintenance charge. These components are generating energy needs to load demands. Then, economic parameters are added, such as inflation and discount rates, and simulation durations are defined. The last step is the selection of the constraints and sensitivity option and the running of the simulation.

3. SELECTED LOCATION AND METEOROLOGICAL CHARACTERISTICS

The province of Kahramanmaras has been selected as the location for this study.Kahramanmaras, a city located in southeastern Turkiye.. With intense solar radiation and long sunny days, it is situated in Turkiye's region with the highest solar energy potential, benefiting from its advantageous geopolitical location [22, 23].

The city has an estimated population of 1,177,436 as of 2022 [24] and is positioned at an elevation of 568 meters above sea level. Kahramanmaras has an average wind speed of 4.74 m/s [25]. The city also experiences an average annual sunshine duration of 7.98 hours per day [26].

Figs. 2 (a) and 2 (b) illustrate the renewable energy potential of the region, with Fig. 2 (a) showing the annual average wind speed distribution at 100 meters and Fig. 2 (b) presenting the annual solar energy potential for Kahramanmaras province. In this study, it is decided to be setup in located at 37° 34.6 ’N and 36°50.3’E coordinates where in the Onikisubat district of Kahramanmaras as shown in Fig. 3. Solar, wind, and temperature data for this location obtained from NASA's Surface Metrology and Solar Energy Database, which is accessed by the Homer pro demo software.

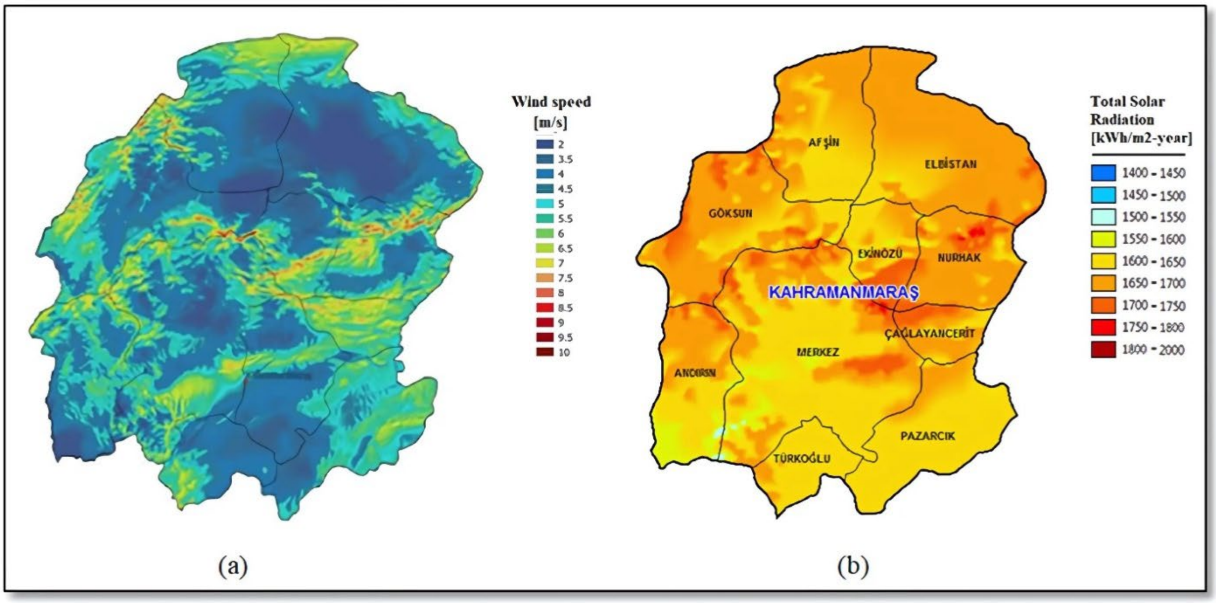


Figure 2. (a) Annual average wind speed distribution in Kahramanmaras (at 100 meters) [25] (b) Solar energy potential atlas of Kahramanmaras [26]

Figure 3. Selected location of the proposed system (generated using google maps)

Average solar irradiance, wind power and temperature data based on months summarizes in Table 1. The data collected is the average over a long period of time, i.e. solar data is the average of data collected from July 1983 to June 2005; wind speed and temperature data is the average of data collected from January 1984 to December 2013. The annual average solar irradiance is 4,65 kWh/m^2/day and the maximum is 7.460 kWh/m^2/day in July. Data indicates that using PV panels can generate electricity in efficient. Also annual average of temperature and wind speed are 11,76 ℃ and 3,82 m/s, correspondingly.

Table 1. monthly meteorological averages for the proposed location

Month	Clearness Index	Solar Irradiance (kWh/m^2/day)	Temperature (℃)	Wind Speed (m/s)
January	0.495	2.300	-0.470	3.830
February	0.519	3.140	0.460	3.940
March	0.521	4.160	4.690	3.840
April	0.498	4.900	9.970	3.600
May	0.548	6.080	15.110	3.540
June	0.628	7.270	20.330	4.250
July	0.662	7.460	24.480	4.520
August	0.648	6.600	24.360	4.150
September	0.638	5.410	19.990	3.710
October	0.595	3.870	14.00	3.370
November	0.522	2.560	6.780	3.410
December	0.475	2.010	1.370	3.630

4. ASSESSMENT OF BIOMASS AVAILABILITY IN THE SELECTED REGION

Biomass, consisting of wood, animal, and plant organic waste, is a valuable resource for energy production. In Turkiye, biomass data is accessible through the Ministry of Energy and Natural Resources' Biomass Energy Potential Atlas (BEPA) [27]. The biomass potential in Kahramanmaras, derived from animal/plant, forest, and municipal sources, was obtained from BEPA data files.

For this study, only municipal biomass is considered, as it can be easily collected and transported by municipal vehicles. The total municipal biomass suitable for biomethanization in Kahramanmaras and its districts amounts to 169,237.80 tons annually. To incorporate this data into the numerical model, the daily biomass quantity was calculated by dividing the annual figure by 365 days, resulting in 463.67 tons/day.

Fig. 4 illustrates the distribution and quantity of municipal biomass available in Kahramanmaras. This data is essential for ensuring accurate inputs in the energy system model and optimizing the use of biomass resources for energy generation.

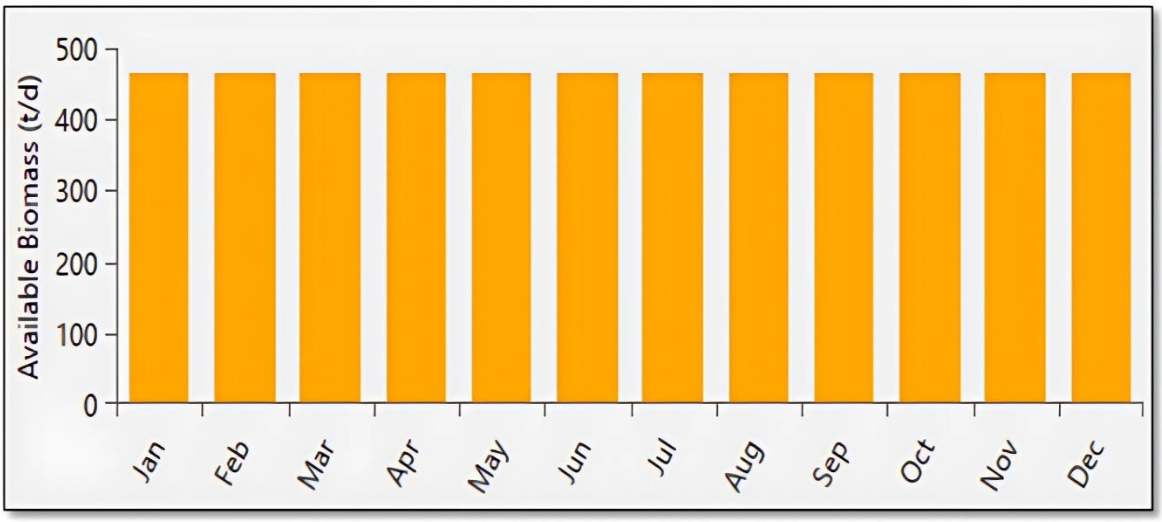


Figure 4. Municipal biomass availability in Kahramanmaras

5. ELECTRICAL LOAD PROFILING: EXPERIMENTAL INSIGHTS

The system has two load demands: hydrogen load and electric load. These load data required in the system are calculated using data EPIAS (Turkish name is an energy exchange company) [28] which provides data on energy markets in Turkiye and Turkstat (Turkiye Statistical Institute). Details of the determination of hydrogen load and electric load (Table 2 and 3) are explained below.

Electricity consumption information in Turkiye can be accessed via EPIAS Transparency Platform [29]. Real time consumption and the percentage of actual consumption by city and customer data are shared on the platform. In this study, Kahramanmaras province 2022 electricity consumption data are used. Due to the large-scale earthquake that occurred in the province in 2023, we preferred to use 2022 data.

Kahramanmaras province electricity consumption data is obtained as follows. First of all, real time consumption (01.01.2022 00:00-31.12.2022 23:00) data of Turkiye (all provinces) is downloaded from the platform. In this way, consumption data of all provinces are accessed at 1 hour intervals. Then Table 2 is created from the monthly percentage consumption information for Kahramanmaras on the platform. Table 2 shows the ratio of Kahramanmaras to all consumption from January to December in 2022. Real-time consumption data was first decomposed into months. From the monthly data, the 24-hour (00:00-23:00) average consumption for the relevant month was calculated. These consumptions were proportioned according to the monthly percentage consumption ratios given in Table 2. And the load profile showing the electricity consumption of Kahramanmaras province as shown in Table 3 was created. The table presents the decimals in their shortest form, rounded to the nearest whole number. The random variability in the load profile is set at 10% from day to day and the time step at 20%. As seen Table 3 that there is a profile with higher consumption at noon and peak consumption value 758.687,259 ≈ 758.687 kWh in March.

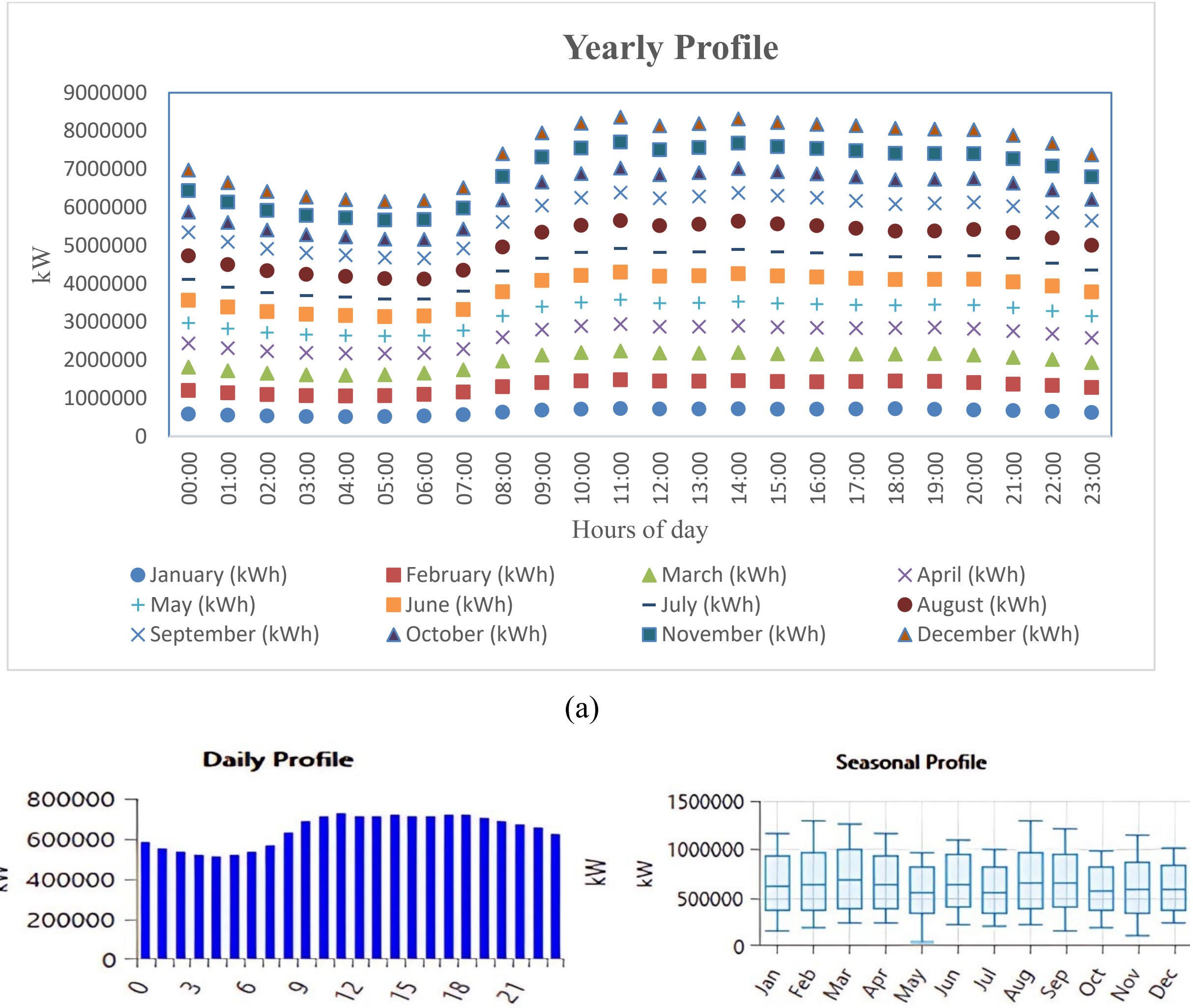
Table 2. Kahramanmaras electricity consumption in comparison to turkey

Month	Consumption Ratio (%)
January	1.69
February	1.76
March	1.76
April	1.80
May	1.68
June	1.69
July	1.49
August	1.52
September	1.76
October	1.71
November	1.77
December	1.64

Detailed load profiles can be seen in Fig. 5. In this fig, the annual average electrical load is 14.946.686,40 kWh/d and peak load is 622.778,60 kW and the load factor is 0,48. The daily profile in Fig. 5b, it is seen that there is energy need at all hours of the day, but it is higher at noon and evening. The reason for this is that the electricity profile includes consumers from all groups rather than a single user profile such as residential, commercial and industrial. As seen in Fig. 5c, the seasonal load profile has maximum power demand in March.

Table 3. Electricity load profile of selected location

Hour/Months	January (kWh)	February (kWh)	March (kWh)	April (kWh)	May (kWh)	June (kWh)	July (kWh)	August (kWh)	September (kWh)	October (kWh)	November (kWh)	December (kWh)
00:00	584.725	615.349	615.921	619.531	536.501	591.512	553.994	608.266	619.437	531.016	557.314	540.476
01:00	554.538	582.804	582.029	593.169	509.634	564.650	528.661	583.425	594.115	509.231	531.461	512.869
02:00	532.928	560.065	559.714	578.311	490.111	543.714	507.810	563.590	576.179	493.323	513.041	493.998
03:00	519.623	547.279	545.917	577.227	477.864	530.246	493.162	548.926	562.143	482.579	501.070	482.086
04:00	514.605	542.937	541.883	570.719	472.227	522.550	484.080	540.672	555.900	479.016	497.347	478.213
05:00	518.186	547.430	549.719	553.937	460.234	505.855	465.737	529.161	553.121	482.776	501.606	482.459
06:00	533.395	564.091	561.444	527.015	455.912	507.836	455.359	514.916	547.508	491.489	518.733	499.180
07:00	567.434	592.249	585.114	543.596	486.165	543.735	484.567	545.665	574.361	509.172	545.363	534.632
08:00	632.789	668.774	673.806	621.614	559.121	630.413	549.614	623.528	655.665	576.562	612.613	596.053
09:00	685.212	720.326	725.791	666.109	602.005	680.702	591.077	673.056	702.082	615.327	653.938	635.890
10:00	711.503	741.174	745.910	687.880	622.976	704.286	614.378	698.248	723.004	632.456	669.228	649.178
11:00	728.472	752.004	758.687	703.663	637.246	719.461	631.524	716.427	738.404	642.069	678.153	656.070
12:00	715.429	732.478	736.725	687.425	618.850	700.818	623.534	703.947	717.545	617.104	649.473	630.425
13:00	715.654	729.994	734.778	690.664	624.026	710.349	633.123	715.891	729.750	625.436	653.894	630.433
14:00	720.155	734.138	741.405	702.645	632.946	725.481	642.901	731.189	747.294	635.572	663.585	637.662
15:00	711.169	724.321	730.160	695.359	623.772	717.356	636.304	725.516	741.128	628.116	655.777	630.504
16:00	709.269	719.865	726.097	689.308	618.216	709.519	629.491	715.412	732.934	626.310	660.513	636.154
17:00	716.206	719.260	718.481	681.241	609.575	692.310	615.481	696.841	719.642	629.769	680.221	659.595
18:00	721.689	724.516	711.454	681.085	598.464	668.442	597.801	671.618	707.996	641.065	685.446	660.403
19:00	707.991	729.873	730.753	680.527	602.051	659.842	596.459	671.431	721.813	636.519	668.153	642.670
20:00	691.052	715.102	723.463	686.508	625.110	674.155	615.662	684.944	713.904	620.886	653.219	628.941
21:00	672.292	695.225	703.629	683.257	617.176	674.555	617.384	672.478	693.763	603.423	636.715	612.770
22:00	652.424	679.065	683.922	669.651	598.322	653.816	602.489	658.996	674.123	584.500	619.732	596.943
23:00	623.942	653.459	656.072	647.108	572.044	628.250	581.572	638.967	647.830	557.720	592.017	572.590



(a)

(b) (c)

Figure 5. (a) Yearly (365days) (b) daily (c) seasonal load profile

6. GREEN HYDROGEN LOAD DEMAND

In addition to the primary electrical load, the system considered in this study incorporates a hydrogen load. To determine the hydrogen load accurately, it is necessary to know the number of hydrogen fuel cell vehicles and their daily travel distances. While direct data on the number of hydrogen vehicles in Kahramanmaras is unavailable, data on vehicle fuel type distribution (gasoline, diesel, LPG, and electric) can be accessed through the Turkish Statistical Institute (Turkstat) [30].

As of November 2023, there are 69,914 electric vehicles (EVs) in Türkiye. Since Kahramanmaras accounts for 1.09% of the total number of vehicles in Türkiye, it is estimated that approximately 763 EVs are located in the city. Assuming that 20% of these vehicles are hydrogen fuel cell vehicles, there would be approximately 150 hydrogen vehicles in Kahramanmaras. For more realistic results, three different hydrogen vehicle models, each with varying tank capacities and travel ranges, were considered. The technical specifications of these models are provided in Table 4.

In 2021, the average annual distance traveled by vehicles in Türkiye was 13,048 km [31], which corresponds to an average daily distance of approximately 36 km. To account for variability in driving conditions, a 25% buffer was added to the predicted travel distance, resulting in an assumed daily travel distance of 45 km for each hydrogen vehicle.

Based on the assumption of 150 hydrogen vehicles, the daily hydrogen consumption for each vehicle model was calculated for a 45 km travel distance. Therefore, the total daily hydrogen requirement for all 150 vehicles is 58.5 kg. This hydrogen demand is critical for accurately designing the hydrogen production system to meet the transportation needs of Kahramanmaras.

Table 4. Technical overview of specific hydrogen vehicles

Model	Range (km/kg)	Tank capacity	Hydrogen requirement of 50 vehicles per day for 45 km
Toyota Mirai [32]	100 km/0,76 kg	6,33 kg	17,1
Hyundai Nexo [33]	100 km/0,84 kg	5,64 kg	18,9
Hyundai İx35 [34]	100 km/1,0 kg	5,64 kg	22,5

As a result of the calculations detailed above, the hydrogen load in the system determined as 58.5 kg. The hydrogen needs of the vehicles are met in the evening after work and it is accepted that vehicles need hydrogen load at 19:00 every day. As seen in Fig. 6, the load profile of hydrogen is constant throughout the year with no seasonal or daily variability.

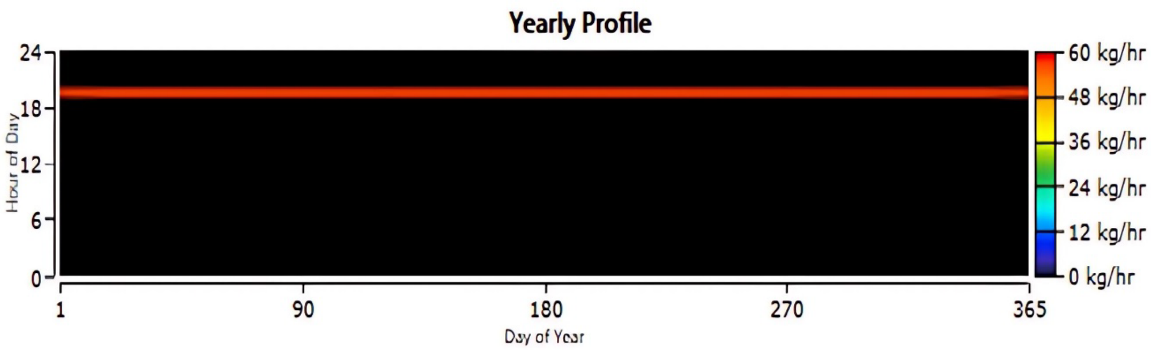


Figure 6. Hydrogen load profile

The determination of real energy charges is a function of economic parameters such as inflation and discount rates. In this way, it is possible to accurately evaluate the real charge and returns of the project. Given that the costs of the components employed in the proposed system are denominated in US dollars, economic estimations are consequently based on US dollar inflation values. In the system, the discount rate for US dollar determined by Turkdogan is taken as 2,25 % [17]. The inflation rate is influenced by various factors, including pandemics and wars. To determine a more realistic value, the inflation rates from the past 10 years (2012–2021) were considered. During this period, inflation rates ranged from 2.07% to 4.7%, with an average of 1.88% [35]. In the model, the inflation rate is set at 2% without any adjustments. The Focus Factor is set at 50, and the project lifespan is planned for 25 years. The typical design life of key system components, such as wind turbines and solar panels, is approximately 20–25 years [36, 37]. During this period, these components operate at optimal efficiency. However, beyond this timeframe, performance begins to decline, maintenance costs increase, and technological upgrades become necessary.

7. CREATED SYSTEM COMPONENTS

7.1. Photovoltaic Plant

Photovoltaic (PV) panels play a crucial role in the system, given the high solar energy potential of the selected location. In this system, the output of the PV panels is connected to a DC electrical bus. Table 5 provides the technical and economic data of the PV panels used in this system, which are 1 kW generic flat-plate panels. The PV panels are assumed to have an economic lifespan of 25 years, with an 80% derating factor. The derating factor accounts for losses in the panel's power output due to factors such as shading, snow covering, wiring losses, and aging. The panels do not include a tracking system, and the panel slope is set at 37.58°. The ground reflectance is assumed to be 20%. The unit price for each kW of PV is 1,000 $/kW, with a replacement charge and operation and maintenance (O&M) charge of 1,000 $/kW and 5 $/kW/year, respectively [36].

Table 5. Techno-economic profile of the photovoltaic model

Parameter	Specification
Rated capacity	1 kW
Panel type	Flat plate
Derating factor	80%
Ground reflectance	20%
Capital Charge	1.000 $/kW
Replacement Charge	1.000 $/kW
O&M Charge	5$ /kW /year
Lifetime	25 years

7.2. Wind Turbine

Wind turbines serve as another critical component for electricity generation. In times when PV panels are insufficient, wind turbines provide substantial support. Given the high electricity demand in the system, such as that required for an entire city, high-power turbines were considered. A 7.58 MW wind turbine manufactured by Enercom was selected. Table 6 provides the technical specifications of the chosen wind turbine. The turbine features a rotor diameter of 127 m and a hub height of 135 meters. The wind turbines are connected to the AC electrical bus. The capital charge for one unit is 18,200,000 $/kW (assuming 1 € = 1 $), with an O&M charge of 490,000 $/kW/year. The wind turbine's lifetime is 20 years [37].

Table 6. Techno-economic profile of the wind turbine model

Parameter	Specification
Rated capacity	7,58 MW
Rotor diameter	127 m
Hub height	135 m
Capital Charge/unit	18.200.000 $/kW
Replacement Charge/unit	0$/kW
O&M Charge/unit	490.000 $/kW /year
Lifetime	20 years

7.3. Biogas Generator

The biogas generator utilizes biogas derived from biomass as its fuel source to generate energy. The generator operates at a capacity of 4,000 kW (AC). The primary cost of the biogas generator is 900 $/kW, with both replacement and maintenance charges set at 900 $/kW and 0.1 $/kW/year, respectively [11]. The features and specifications of the selected biogas generator are outlined in Table 7.

Table 7. Techno-economic profile of the biogas generator model

Parameter	Specification
Capacity	4.000 kW
Capital Charge/unit	900,00 $/kW
Replacement Charge/unit	900,00 $/kW
O&M Charge/unit	0,10 $/kW /year
Minimum load ratio	50 %
Lifetime	20.000 hours

7.4. Electrolyzer

The electrolyzer is used to generate hydrogen by separating water into hydrogen and oxygen molecules through electrolysis. The hydrogen produced is stored in a hydrogen tank. In this study, a 1,000 kW generic electrolyzer with an efficiency of 85% was selected. The capital charge for the electrolyzer is 1,400 $/kW, with an O&M charge of 28 $/kW/year, while the replacement charge is neglected [38]. Table 8 presents the technical specifications and economic feasibility of the selected electrolyzer model.

Table 8. Electrolyzer model: technical specs and economic feasibility

Parameter	Specification
Rated capacity	1.000 kW
Efficiency	85%
Capital Charge	1.400 $/kW
Replacement Charge	0 $/kW
O&M Charge	28 $/kW /year
Lifetime	15 years

7.5. Li-ion Batteries for Energy Storage

Renewable energy is stored in lithium-ion (Li-ion) batteries when the generated power exceeds the system's load demand. Batteries also support the system during periods of low renewable energy generation, such as cloudy days or nighttime. Li-ion batteries were selected due to their long lifespan, high efficiency, and lower minimum charge requirements. In this system, generic 1 MWh Li-ion batteries were used. Table 9 outlines the technical specifications and economic feasibility of the selected battery system. The capital and replacement charges for the batteries are assumed to be 700,000 $.

Table 9. li-ion batteries system: technical specifications and economic feasibility

Parameter	Specification
Rated voltage	600 V
Rated capacity	1670 Ah
Round-trip efficiency	90%
Capital Charge	700.000 $
Replacement Charge	700.000 $
O&M Charge	10 000 $/ year
Lifetime	15 years

7.6. Hydrogen Tank

The green hydrogen produced by the electrolyzer is stored in a hydrogen tank for use in vehicles. The system incorporates a 120 kg hydrogen tank, which is approximately twice the daily load requirement. Additional storage is included to account for periods when hydrogen production is insufficient. Given that the system's daily hydrogen requirement is 58.5 kg, the 120 kg tank provides sufficient capacity. The capital charge for the hydrogen tank is 1,000 $, and its lifetime is 25 years, with no replacement or O&M charges [39].

Table 10. hydrogen storage tank: technical specifications and economic feasibility

Parameter	Specification
Capacity	120 kg
Capital Charge	1.000 $
Replacement Charge	0 $
O&M Charge	0 $
Lifetime	25 years

7.7. Converter

The converter facilitates the energy transfer between DC and AC power. Biogas generators and wind turbines are connected to the AC bus, while batteries and PV panels are connected to the DC bus, providing energy to the system. The converter ensures the proper transfer of energy between these components through bidirectional AC-DC conversion. The efficiency of the selected converter is 95%, with a capital charge of 300 $/kW and a replacement charge equal to the initial charge. No O&M charge is assumed for the converter, and its lifetime is 15 years [40].

Table 11. converter model: technical specifications and economic feasibility

Parameter	Specification
Efficiency	95%
Capital Charge	300 $
Replacement Charge	300 $
O&M Charge	0 $
Lifetime	15 years

8. ECONOMIC PARAMETERS OF PROPOSED NUMERICAL ANALYSIS

In order to obtain the optimum system, the simulation program first determine whether it is feasible to provide the specified loads and then presents the optimum system results according to the economic parameters [40]. The two major parameters used by researchers to determine the optimal solution are Net Present Charge (NPC) and Charge of Energy (COE). NPC refers to the present value of all revenues and charges (operation, maintenance and fuel charges) over the lifetime of the components, NPC is calculated as follows:

$$NPC = \frac{C_{an,total}}{CRF(i, P_L)} \tag{1}$$

where $C_{an,total}$ is the total annualized charge ($/yr), i is the annual real discount rate (%), P_L is the project's lifespan (year), and $CRF(i, P_L)$ is the capital recovery factor [41].

The term Charge of Energy (COE) refers to the average charge per kilowatt-hour (kWh) of useful electrical energy generated. The calculation of COE involves the use of the annual charge (AC). It is represented in mathematical form by the equation:

$$AC = CRFxNPC \tag{2}$$

CRF is the capital recovery factor and it is calculated as follows:

$$CRF(i, n) = \frac{i\,(1+i)^n}{(1+i)^n - 1} \tag{3}$$

where 'i' and 'n' represent the discount rate (annual) and years respectively. Real discount rate 'i' is found by as follows:

$$i = \frac{i^* - f}{1 + f} \tag{4}$$

where ‘i^*’ is the nominal rate used in money transactions and ‘f’ is the inflation rate [42].

Using AC and the served energy (E_s), the charge of energy (COE) can be calculated as follows:

$$COE = AC \frac{yr}{E_s(kWh/yr)} \tag{5}$$

where yr working year [43].

9. NUMERICAL ANALYSIS AND OPTIMIZATION RESULTS

The numerical analysis evaluates all feasible combinations of system components, optimizing the configuration while considering the associated costs in US dollars. A total of 14,550 simulations were conducted, and 2,870 optimization cases were analyzed to determine the optimal system structure. The optimization results, shown in Figure 7, reveal the best-performing hybrid system configuration. The optimized system comprises the following components:

- 13,255,685 kW of photovoltaic (PV) panels,
- 280 wind turbines, each with a 7.5 MW capacity,
- A 4,000 kW biogas generator,
- A 1,000 kW electrolyzer,
- 20,096 strings of 1 MWh Li-ion batteries,
- A 120 kg hydrogen storage tank,
- 1,703,726 kW of converters.

The total Net Present Cost (NPC) of the system over the project lifetime is calculated to be 52,270,950,000 USD, with an annual operating charge of 798,318,300 USD/year. The Levelized Cost of Electricity (LCOE) for the system is determined to be 0.3959 USD/kWh. Notably, the system operates with a 100% renewable fraction, meaning all the electricity supplied to the load is generated from renewable sources. Table 12 presents a summary of the techno-economic values for each component of the proposed hybrid system. It is evident from the table that the most significant portion of the expenses comes from the Li-ion batteries, which account for a substantial portion of the capital cost.

Architecture								Cost		
PV (kW)	E-126	Bio (kW)	1MLI (#)	Electrolyzer (kW)	HTank (kg)	Converter (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)
13,255,685	280	4,000	20,096	1,000	120	1,703,726	LF	$52.3B	$0.396	$798M
14,193,944	256		20,000	1,000	120	1,552,484	CC	$52.3B	$0.396	$785M
20,424,901	60	4,000	22,156	1,000		2,521,055	CC	$57.0B	$0.432	$793M
20,909,133	65		21,836	1,000		2,529,166	CC	$57.2B	$0.433	$786M
18,806,839		4,000	27,364	1,000		1,732,526	CC	$60.3B	$0.456	$899M
18,806,839		4,000	27,364	1,000	120	1,732,526	CC	$60.3B	$0.456	$899M
18,684,011			28,027	1,000		1,961,607	CC	$61.1B	$0.463	$916M
17,145,489			29,462	1,000	120	1,524,480	CC	$61.2B	$0.463	$946M
	1,875	4,000	34,244	1,000	120	2,979,177	CC	$106B	$0.801	$1.93B
	1,909		34,028	1,000	120	2,968,671	CC	$106B	$0.806	$1.94B

Figure 7. Optimization results for according to the determined energy load demands

Table 12. Key technical and financial metrics of the created main model

Component	Rated Capacity	Capital (USD)	Replacement (USD)	O&M (USD)	Total (USD)
PV Panel	13.255.685 kW	13.255.684.613	0	1.605.310.166	14.860.994.779
Wind [7.5MW]	1.940.480 kW	5.096.000.000	0	3.323.080.795	8.419.080.795
Generic 1MWh Li-ion Battery	20.096 string	14.067.200.000	13.560.024.940	4.867.392.977	28.083.915.229
Converter	1.703.726 kW	511.117.802	492.690.098	0	843.549.380
Electrolyzer	1.000 kW	1.400.000	0	678.179	2.078.179
Generic Biogas Generator	4.000 kW	3.600.000	17.404.300	42.124.651	61.215.698
Hydrogen Tank	120 kg	120.000	0	0	120.000
Main System		32.935.122.416	14.070.119.339	9.838.586.770	52.270.954.062

Fig. 8 illustrates the details of the energy sources and monthly average electricity generation. In this figure, "PV" refers to electricity generated from photovoltaic panels, "E-126" represents electricity produced by wind turbines, and "Bio" signifies electricity from the biogas generator. The contribution of each energy source to total electricity generation is as follows:

- 89.4% (20,115,067,950 kWh/year) from PV panels,
- 10.5% (2,373,771,477 kWh/year) from wind turbines,
- 0.0772% (17,385,430 kWh/year) from the biogas generator.

The generated electricity from PV panels and wind turbines peaks during the summer months (June, July, and August). The electricity generated from renewable sources is consumed as AC primary load (5,451,768,865 kWh/year) and by the electrolyzer to meet the hydrogen load. Any excess energy is stored in the Li-ion batteries. Notably, 100% of the electricity consumption is fulfilled by renewable energy sources.

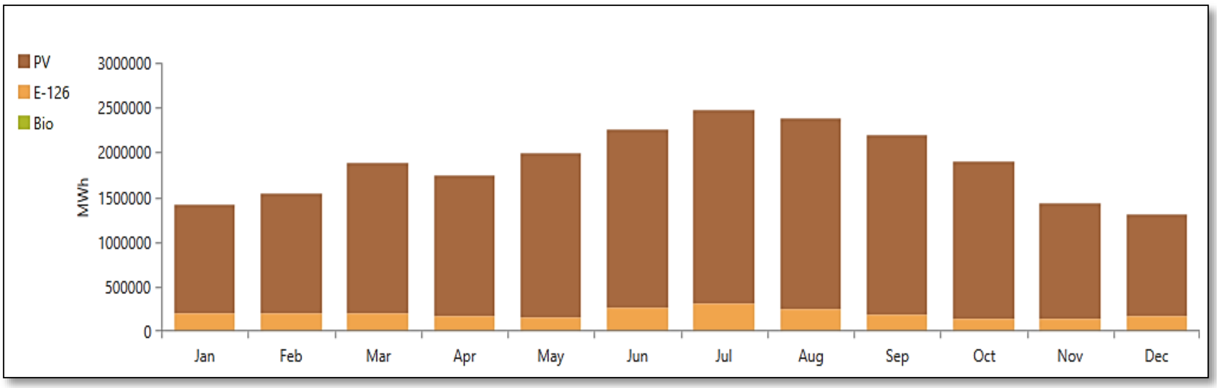
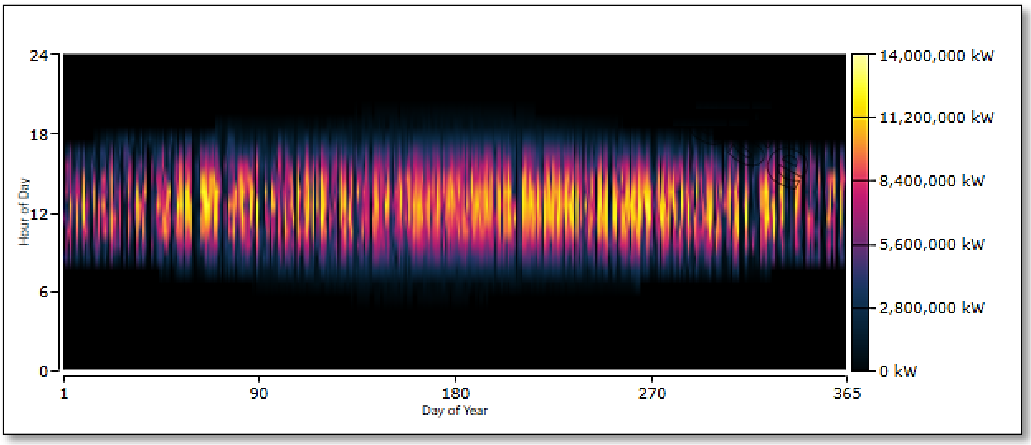
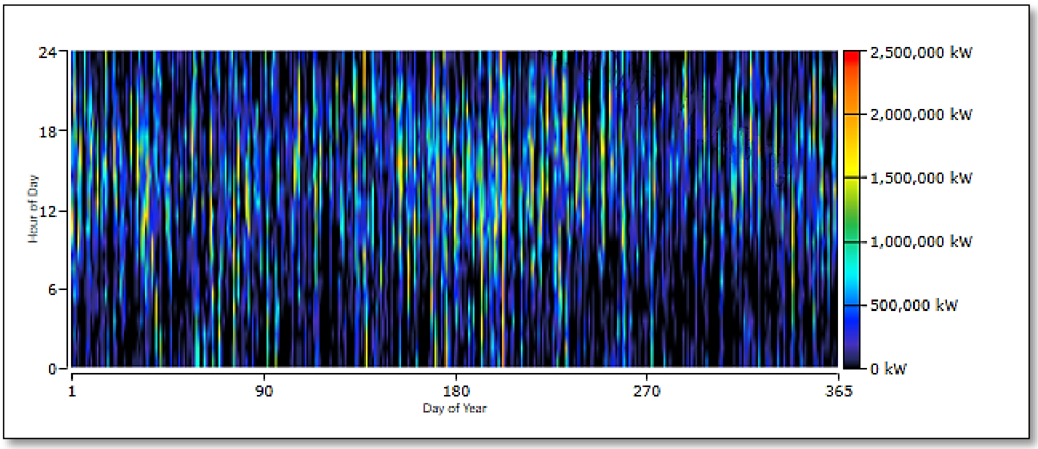


Figure 8. Monthly electricity generation distribution according to the energy sources

The power output of the PV and wind turbines throughout the year is shown in Fig. 9. By analyzing Figure 9, it can be seen that the PV panels generate more power at noon and in the summer because of the greater amount of solar radiation and the longer hours of sunshine. In the part shown in black in the graph, PV panels cannot generate any power at night, that is, when there is not solar radiation. Wind turbines generally generate electricity throughout the year, but more electricity is generated in the middle of the year.



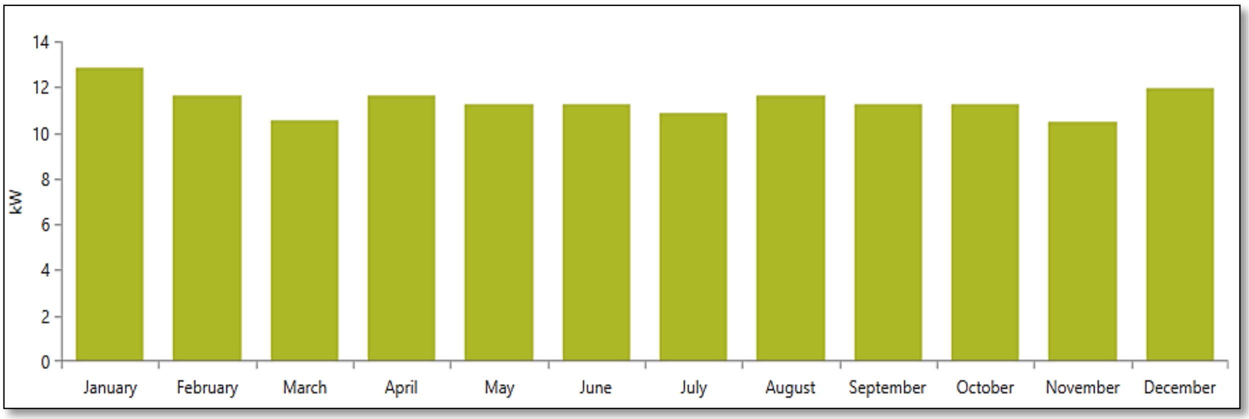
(a)



(b)

Figure 9. The yearly a) photovoltaic b) wind turbine power outputs

As illustrated in Fig.10, 1.000 kW Electrolyzer was used in the system and output of the electrolyzer was found to be 4158 kg per year. The electrolyzer's average and maximum capacities are 0.0475 kg per hour and 21.5 kg per hour, respectively. The average input is 22 kW. In one year, the electrolyzer consumed 192.966 kWh of renewable energy and calculated capacity factor is 2.20%. The electrolyzer operated for 396 hours of the year.



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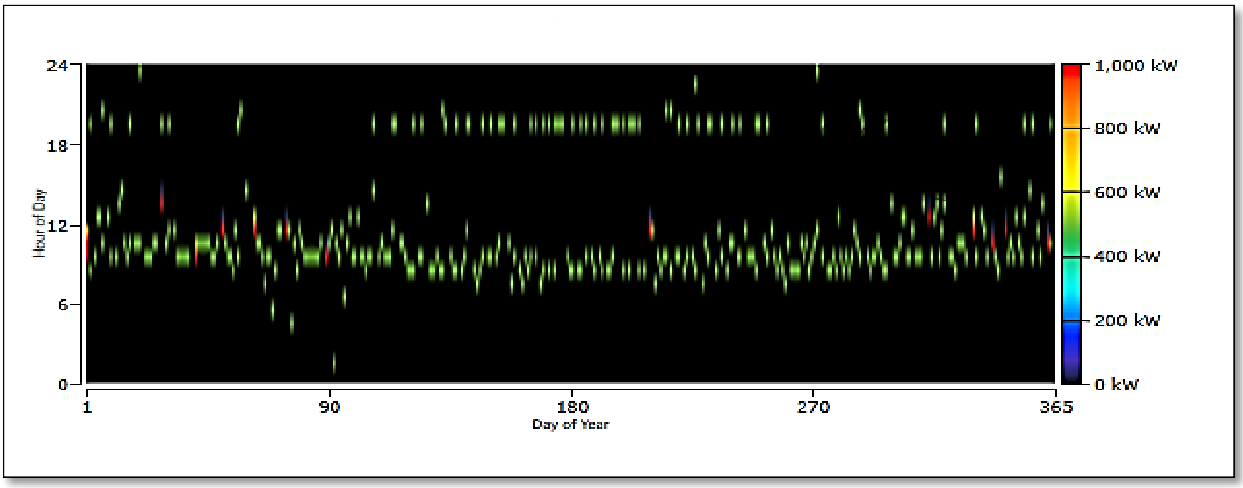


(b)

Figure 10. (a) Electrolyzer power per month (b) yearly electrolyzer input power

The optimum system consists of a 1MWh Li-ion battery with a bus voltage of 600 V. The nominal battery capacity is 200.960.04 kWh, but because of 80% depth of discharge (DOD), the usable nominal capacity is 160,768.03 kWh. During lifetime of the battery bank, 13.171 kWh of energy was stored. 2.108.558.851 kWh/year of energy was output from the batteries, which had an energy input of 2.337.851.342 kWh/year. The annual charge status of the batteries is shown in Fig. 11.

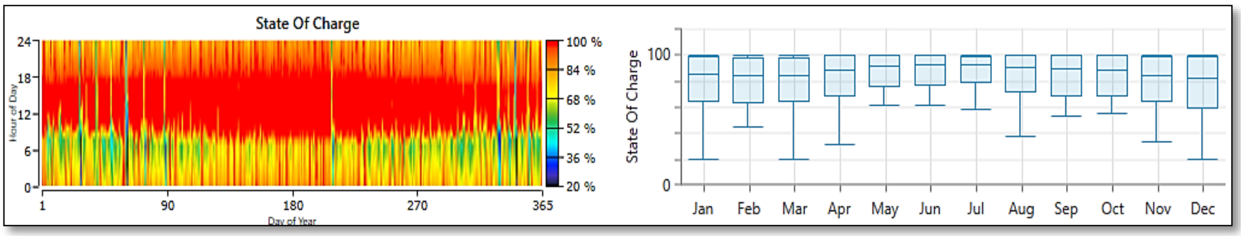


Figure 11. Annual state of charge of li-ion batteries

In the proposed system, the 120 kg hydrogen tank starts with 60 kg of hydrogen at the beginning of the year and ends with 109 kg at the end of the year, indicating that the system provides adequate power. Figure 12 illustrates the annual hydrogen tank level, showing that hydrogen production primarily occurs during daylight hours due to solar radiation, but continues throughout the day. At 19:00, the tank level decreases due to the planned hydrogen load. The electrolyzer is then activated at the appropriate times, in accordance with the electrical load demand in the system, to generate additional hydrogen.

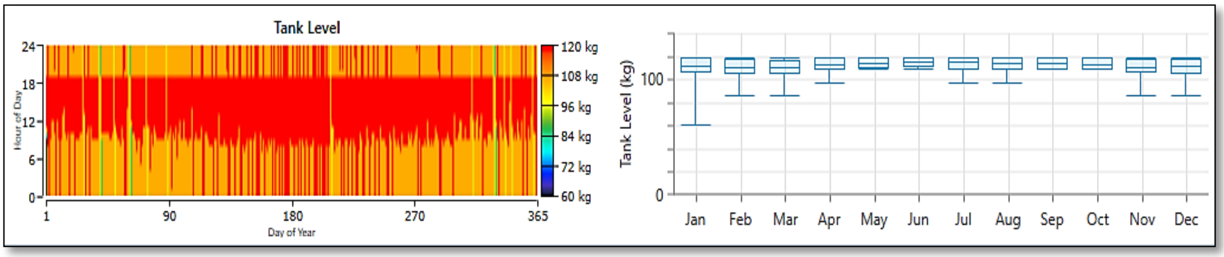
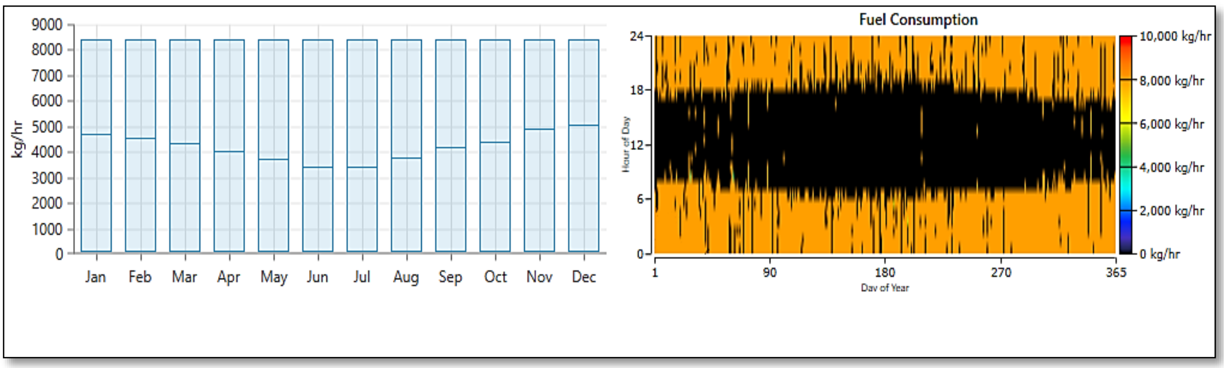


Figure 12. Yearly hydrogen tank level

Figure 13 (a) displays the fuel consumption of the biomass gasifier over the course of a year. The total fuel consumption for the year is 52 .157 tons, with an average daily consumption of 143 tons and an average hourly consumption of 5,95 tons. As shown, fuel consumption decreases during summer months, but remains high throughout the year. In Figure 13 (b), the electricity production of the biomass gasifier is presented for a year. The biomass gasification system generates a total of 17.385.430 kWh of electricity per year. The average electrical output is 3998 kW, while the minimum and maximum outputs are 2000 kW and 4000 kW, respectively. The system's fuel consumption is 52.157 tons, with a specific fuel consumption of 2.10 per kWh. The biomass gasifier operates for 4348 hours annually, and the system's average electrical efficiency is 31.2 %.



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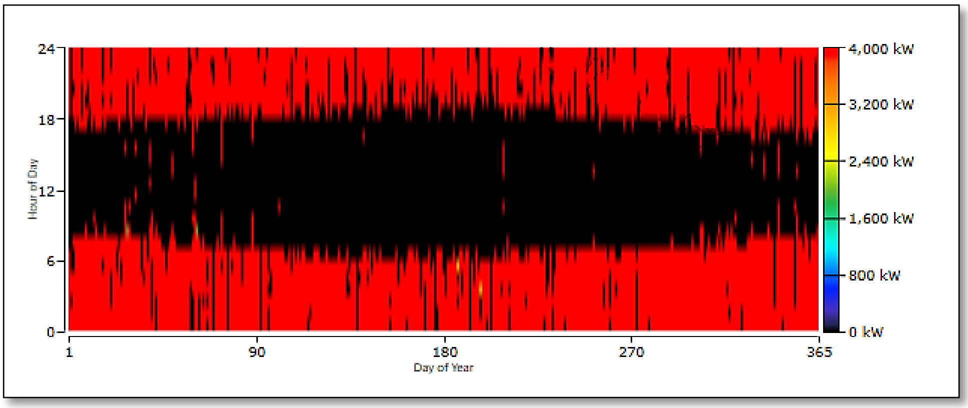

(b)

Figure 13. (a) Biogas fuel consumption (b) yearly biogas generator power output

10. ENVIRONMENTAL BENEFITS AND CHALLENGES OF THE CREATED ENERGY MODEL

This represents a key objective of the proposed study. In order to attain a green and more sustainable world, it is crucial to reduce greenhouse gas emissions as it known. CO_x, NO_x and SO_x are dangerous gases and should be reduced as much as possible [44]. Homer emission values of the proposed system are presented in Table 13. As seen, carbon dioxide (CO_2) will decrease by 9.398 kg, carbon monoxide by 104 kg and nitrogen oxides by 62,5 kg per year, respectively. However, we make a different calculation for CO_2. Because in addition to electricity generation, the transportation sector also has an impact on carbon dioxide production. In other words, choosing hydrogen vehicles instead of diesel, gasoline or LPG vehicles makes a significant contribution to reducing greenhouse gas emissions. For this reason, the emission from using hydrogen vehicles (E_{HV}) is added to the emission from hybrid system electricity generation (E_{HSEG}). So we can be calculated total emission (E_T) as follows:

$$E_T = E_{HSEG} + E_{HV} \tag{6}$$

Table 13. Yearly emission outcomes of the created hybrid energy model

Quantity	Value (kg/year)
Carbon Dioxide (CO_2)	9.398,00
Carbon Monoxide (CO)	104,00
Unburned Hydrocarbons	0
Particulate Matter	0
Sulfur Dioxide	0
Nitrogen Oxides	65,2

Diesel vehicles are the most widely used fuel type in Turkiye [30]. The CO2 emissions per liter for diesel 2640 g CO_2 /liter and assuming an average fuel consumption of 5 liters per 100 kilometers, the emissions per kilometer would be 132 g CO_2/km for diesel [45]. In this study, assumed a total of 150 hydrogen vehicles is considered. Each vehicle is traveling 45 km per day. If calculations are based on this information;

132 g CO_2/km *45 km/day=5,94 kg CO_2/day
5,94 kg CO_2/day*365 day= 2.168,100 kg CO_2/year
2168,100 kg CO_2/year*150=325.215 kg CO_2/year (for 150 hydrogen vehicle)

If the vehicle used had been a diesel, it would have generated 325.215 kg CO_2 per. Total CO_2 emission saving for hydrogen vehicles instead of diesel are 334.613 kg =334,613 tons from eq. (6).

Fig. 14 presents the annual diagram of greenhouse gas savings, segmented into three columns based on the fuel type used in vehicles. The transition from diesel vehicles to hydrogen vehicles results in the highest overall savings.

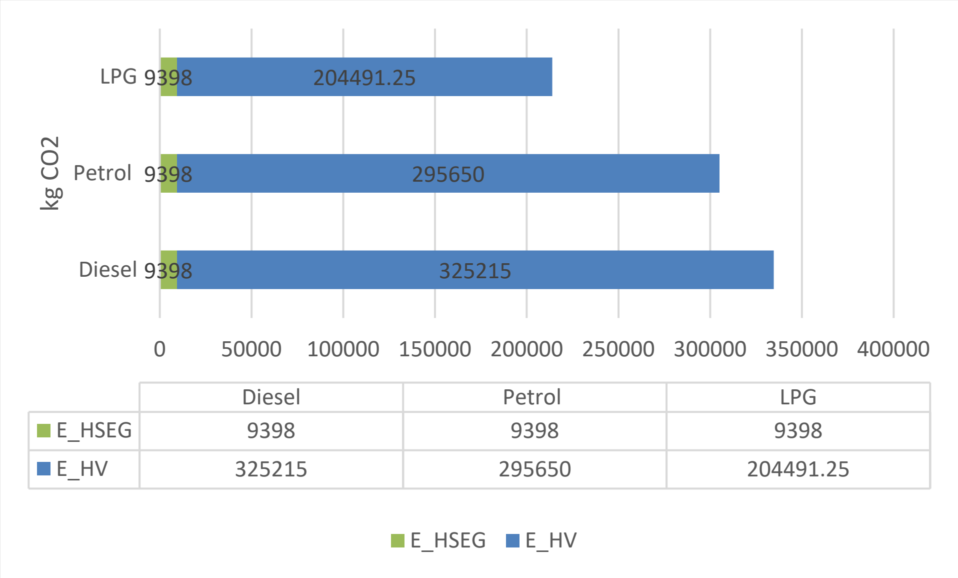

Figure 14. Total yearly emission HSEG and HV

The same calculations can easily be made for petrol or LPG vehicles. the CO_2 emissions per liter for petrol and LPG are 2392 g CO_2 /liter, and 1665 g CO_2/liter, respectively. Based on an average fuel consumption of 5 liters per 100 kilometers, the emissions per kilometer are 120 g CO_2/km for petrol and 83 g CO_2/km for LPG [45]. As a result of the calculations, if petrol or LPG vehicles were used instead of hydrogen vehicles, 295.650 kg of CO_2 and 204.491,25 kg of CO_2 emissions would be caused per year, respectively.

In related studies, hybrid systems predominantly rely on solar and wind resources, while other renewable sources such as hydropower, batteries, and biomass are integrated in various combinations. In this regard, our study aligns with existing research in the field. Previous studies range from small-scale applications, such as meeting the electricity and hydrogen fuel needs of a single household, to large-scale energy solutions at the provincial level. In our study, the daily production of approximately 60 kg of hydrogen stands out as a significant achievement, demonstrating the feasibility of large-scale hybrid energy systems.

11. CONCLUSION

This study presents a comprehensive techno-economic analysis of a large-scale hybrid energy system based on renewable energy sources. The hybrid system is designed to fulfill two primary objectives: first, to meet the electricity load demand of Kahramanmaras province without relying on the grid, utilizing real load data; and second, to satisfy the hydrogen demand for 150 hydrogen vehicles assumed to be used for urban transportation.

The integration of renewable energy sources for both electricity generation and hydrogen production plays a pivotal role in significantly reducing carbon emissions. The proposed hybrid system consists of photovoltaic (PV) panels, wind turbines, and a biogas generator for electricity production, along with Li-ion batteries, an electrolyzer, and a hydrogen tank for energy storage and hydrogen production. The inclusion of biogas generators is essential for the conversion of biomass into energy, which contributes to sustainable urban energy solutions. While the contributions of the biogas generator and wind turbines to the total electricity generation are relatively small, they serve a critical role in ensuring energy supply when PV generation is insufficient. The PV panels remain the dominant source of electricity, contributing 89.4% of the total energy generation.

One of the key limitations of the proposed system is its high initial cost, which can be mitigated through government incentives and grants. In Turkey, foreign investor incentives, YEKDEM, and domestic equipment incentives play a crucial role in this regard [46, 47]. Additionally, advancements in technology are driving down the costs of system components. For example, the average cost of PV modules has significantly decreased from 2.65 USD/W in 2010 to 0.306 USD/W in 2020 [48]. The continuous decline in the costs of PV panels, wind turbines, and batteries—the most expensive components of the system—will enhance its economic feasibility over time.

The results of the optimization process, derived through numerical analysis, yield a Cost of Electricity (COE) of 0.3959 USD and a Net Present Cost (NPC) of 52.3 billion USD. It is anticipated that the unit cost of electricity generation will decrease further in the future due to reductions in component prices driven by technological advancements.

The proposed system has the potential for application not only in Kahramanmaras but also in other regions and countries. The cost of the system can be further reduced in locations with higher solar radiation and average wind speeds. To achieve a more efficient and cost-effective system design, integrating additional renewable energy sources such as geothermal and hydropower is recommended. For example, in Turkey's Aegean Region, where geothermal resources are abundant, or in the Eastern Anatolia and Black Sea Regions, where hydropower potential is substantial, these resources can be incorporated into the system to enhance energy diversity and resilience. Additionally, the integration of smart energy management systems is expected to improve efficiency by optimizing resource utilization and demand response. Future research can expand on these aspects to develop more comprehensive and adaptive hybrid energy solutions.

Moreover, the environmental impact analysis of the proposed system demonstrates that the use of a hydrogen-integrated hybrid system for electricity generation, combined with the adoption of hydrogen vehicles, can significantly mitigate CO_2 emissions, contributing to a greener and more sustainable future.

The study further expands its scope by evaluating scenarios involving vehicles with varying tank capacities and ranges. While the number of 150 hydrogen vehicles may appear modest for a city, it represents a substantial figure for a newly established and growing vehicle fleet. The proposed system is capable of effectively meeting the fuel demands of a considerable number of hydrogen vehicles on a daily basis, thereby promoting the transition to clean transportation. Additionally, the model is flexible and can be adapted to other cities, offering a scalable solution for renewable energy integration. The results also suggest potential opportunities for expanding green hydrogen production and creating market-based strategies in line with the growing demand for sustainable energy solutions.

In conclusion, this study, which emphasizes the use of renewable energy sources for both residential electricity and transportation needs, provides a valuable reference for creating a sustainable energy system. It not only addresses the immediate energy needs of a region but also contributes to the broader goals of carbon reduction and environmental sustainability.

NOMENCLATURE

AC: Annual charge

BEPA: Biomass energy potential atlas

COE: Charge of energy

CRF : Capital recovery factor

DOD: Depth of discharge ,

E_{HV} : Emission from using hydrogen vehicles

E_{HSEG} : Emission from hybrid system electricity generation

EPIAS :Turkish name is an energy exchange company

E_T : Total emission

EVs : Electric vehicles

$\boldsymbol{f}$**:** inflation rate

HRES: Hybrid renewable energy system

HOMER : Hybrid optimization of multiple energy resources

$\boldsymbol{i}$ **:** annual discount rate

LCOE : Levelized cost of electricity

Li-ion : Lithium-ion

PV : Photovoltaic

NPC : Net present cost

O&M : Operation and maintenance

Turkstat: Turkiye statistical ınstitute

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Furkan Dincer: Conceptualization, Methodology, Supervision.

Emre Ozer: Writing, Methodology, Investigation, Analysis, Software, Visualization.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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