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RESEARCH ARTICLE

Techno-Economic Comparative Analysis of Grid-Connected and Islanded Hybrid Renewable Energy Systems in 7 Climate Regions, Turkey

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ABSTRACT The aim of this study is to evaluate the economic, technical, and environmental performances of grid-tied and stand-alone hybrid renewable energy systems (HRESs) in 21 provinces in seven regions of Turkey, considering different regional solar radiation and wind speed diversity. HRES were designed and modeled using the Hybrid Optimization of Multiple Energy Resources software (HOMER PRO) to meet the daily load of 13.26 kWh/day of a household. The analysis results for each province were compared considering the cost of energy, net present cost (NPC), greenhouse gas emissions, renewable fraction (RF), and optimum system configuration. The findings demonstrated that the optimal system configurations are Grid/PV/WT and PV/WT/DG/BESS for grid-tied and stand-alone HRES, respectively. The value of NPC ranges from $2,540.00 to $8,951.00 for grid-tied HRES, while it varies from $23,372.00 to $40,858.00 for stand-alone HRES. The provinces of Çanakkale in the Marmara Region and Artvin in the Black Sea Coast Region have the lowest and highest NPC values, respectively, for all systems. The PV capital cost, WT capital cost, BESS capital cost, solar radiation, and wind speed are considered as sensitivity input parameters that might affect the economic output of the HRES in this study. According to the sensitivity analysis, the NPC value as an economic indicator input decreased for both on-grid and off-grid HRES as the wind speed and solar radiation increased. It was also found that when the capital cost of PV panels and WT were changed, the NPC of the stand-alone HRES was in the range of $21,402.27-$29,978.89 for the province of Çanakkale, while it was in the range of $37,518.11-$51,939.00 for the province of Artvin. Moreover, when solar radiation and wind speed were increased, the results showed that NPC and CO_2 emissions decreased by 9.30% and 9.23%, respectively, for Çanakkale, and by 25.58% and 66.95%, respectively, for Artvin. Finally, the results indicated that the optimal system configuration changes depending on the PV and WT capital cost variations for the grid-tied HRES. This research can be useful for planning grid-tied and stand-alone HRES from different aspects in Turkey, as well as other countries around the world. It contributes to the literature by comparing grid-tied and stand-alone HRES to determine the optimum system configuration and to find the best optimization results in seven regions of Turkey under different climate conditions. In addition, most of the studies related to HRES for residential areas in the literature are reviewed in this research, which intends to serve as a guide for engineers and researchers.

INDEX TERMS Cost of energy, greenhouse gas, HOMER ® software, hybrid renewable energy system (HRES), net present cost, techno-economic optimization.

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I. INTRODUCTION

The use of energy resources has become one of the most important issues worldwide, increasing rapidly in processes from the industrial revolution to the present day [1]. The global need for energy continues to increase day by day. While the world's energy demand was approximately 3 quadrillion British Thermal Units (BTUs) at the beginning of the 18th century, it reached nearly 100 quadrillion BTUs in 2010 [2].

According to the International Energy Outlook (IEO), global energy demand is expected to rise significantly between 2012-2040. The total global energy consumption increased from 549 quadrillion BTUs in 2012 to 629 quadrillion BTUs in 2020. It is projected to reach 815 quadrillion BTUs by 2040 [3]. This indicates that there will be a 48% increase in global energy consumption in the world between 2012-2040. Due to limited fossil fuels, increasing energy demand and costs, and greenhouse gas emissions that cause global warming, studies on the use of energy from renewable energy resources (RES) at national and global levels have gained momentum to increase the share of renewable energy within the scope of both SDG7 (Sustainable Development Goals) and the Paris Agreement. However, because of the intermittent nature of RES, a hybrid system to be established with renewable energy sources must be designed to ensure energy reliability. With hybrid renewable energy systems (HRESs), the stability and reliability of energy systems can be increased, emissions of greenhouse gases released into the atmosphere can be reduced, and energy can be used efficiently by reducing operating costs.

Turkey ranks second in the world among the Organization for Economic Cooperation and Development (OECD) countries after China, where the demand for electrical energy has increased in the last 20 years. Increasing the share of domestic and renewable energy in electricity generation is one of the main objectives of Turkey's energy strategy, as Turkey is dependent on imports to meet its energy demand by 74% [4]. As a result of the increase in the use of energy resources, the need for fossil fuels is rapidly increasing [5]. Since the use of fossil energy sources such as oil, natural gas, and coil has led to global warming and increased carbon emissions, studies have been conducted on a global scale to increase the use of alternative energy sources. RES such as solar, wind, biomass, and hydrogen, which can be used as alternatives to fossil fuels, have begun to be preferred for a cleaner environment. RES have become preferred over fossil-based sources because of their improved power supply, decreasing dependence on fossil fuels, reducing greenhouse gas emissions, diversifying supply, enhancing long-term access, and inexhaustibility [6].

The importance and use of RES, which meet net zero-emission targets, is increasing daily because of fossil-based fuels that cause global warming and climate change. Thus, 196 countries, including Turkey, signed the Paris Climate Agreement in 2016, within the scope of the United Nations Framework Convention on Climate Change (UNFCCC).

According to the agreement, the aim is to reduce carbon and local emissions by 2050 [7], [8]. Decarbonization efforts worldwide and in our country are only possible through the adoption of renewable energy systems and technologies. Studies that will contribute to Turkey's achievement of these goals are possible with the design of HRES based on geographical conditions.

The use of wind and solar energy among RES is increasing day by day depending on factors such as technological developments, reduction of costs, policies, and strategies implemented by governments regarding renewable energy. Owing to CO_2 emissions, rising prices of fossil fuels, dependence on external sources, an increase in the installation of wind power plants, and an increase in the use of photovoltaic (PV) panels is expected in Turkey [9]. For a sustainable environment in the world, studies continue to rapidly reduce harmful gas emissions from fossil energy sources and reduce local emissions by 100% by 2050. Expanding renewable energy sources, reducing their costs, enhancing incentives, and promoting R&D activities in renewable energy technologies are of great importance for sustainable economic growth [10]. Wind and solar-based renewable energy technologies are strongly dependent on weather conditions. Therefore, ensuring the continuity of renewable energy is crucial. In this context, hybrid energy systems (HESs) and microgrid systems play an important role in ensuring energy sustainability.

In addition to sustainability problems, the high initial costs and low efficiency of renewable energy systems should also be considered [11].

The solution to this challenge is to develop a hybrid system consisting of different energy sources and storage technologies. A HRES with a battery energy storage system (BESS) meets the energy demand and ensures energy continuity [12], [13]. Hybrid renewable energy systems may be designed as either grid-connected or stand-alone. Stand-alone HRES, also known as off-grid, islanded, microgrids, or remote in the literature, is a system used when grid energy is temporarily not available. Renewable energy sources can deliver the required power in stand-alone HRES. In addition, diesel generators (DGs) and battery systems are included to ensure energy continuity [14].

Grid-connected HRES are also known as on-grid, grid-tied, or grid-assisted in the literature. Because renewable energy sources are heavily dependent on the weather, the required power is supplied from the AC grid in cases where these renewable energy sources cannot meet the energy demand in grid-connected HRES [15].

A HRES can be designed as grid-connected and stand-alone, ensuring grid reliability and flexibility while providing uninterrupted energy needs in rural areas as well.

HRES have important effects on reducing greenhouse gas emissions for a cleaner environment and reducing dependence on external sources from an economic point of view. Whether grid-connected or islanded, the reliability and flexibility of the system can be provided by the local renewable resources. In this study, HRES in different provinces of Turkey were compared both economically and environmentally. A proper techno-economic analysis can provide a comprehensive evaluation of the attributes of energy technologies using key features such as system boundaries, cost and benefit analysis, and sensitivity analysis. In addition, it is also within the scope of this study to decide on the most suitable technology set for the HRES to be used in selected provinces, to size them appropriately, to minimize the operating and capital costs of the system, and to make the system reliable and flexible.

Wind and solar energy are among the renewable energy sources considered important for sustainable development and are widely used in developed countries [16]. In recent years, there has been a significant increase in the solar energy capacity in Turkey. Owing to its climate zone, it can benefit from solar energy at a higher rate. Turkey has a high solar and wind energy potential. Therefore, it is predicted that investments in these types of energy can quickly pay for itself and provide high efficiency in energy production [17], [18].

The key motivations of this research are described below:

- To pinpoint the renewable energy potentials in 21 different provinces of Turkey.
- To review residential studies in the literature in terms of their drawbacks and contributions to the domain of energy system.
- Determine the optimum grid-tied and stand-alone HRES configurations at various locations in Turkey.
- To evaluate the effects of HRES from technical, economic and environmental aspects.
- To compare the provinces selected for this study in Turkey in terms of renewable fraction (RF) and CO_2 emissions, primarily in the net present cost (NPC).
- To conduct a sensitivity analysis of HRES based on capital cost parameters, solar radiation, and wind variation, considering techno-economic indicators.

This study is mainly conducted to achieve three objectives. The first objective of this research is to determine the most suitable grid-tied and stand-alone HRES that yield the minimum system cost and lowest emissions. The second objective is to choose the optimal locations for HRES in different regions of Turkey. The third objective is to examine how the uncertainty of the key variables affects the optimal HRES configuration.

The remainder of this study is organized as follows: Solar and wind energy potential in Turkey are explained in Sections II and III, respectively. Section IV describes HRES studies for residential areas in the literature. Section V discusses the input parameters used for the simulation in detail. Simulation results and discussion are presented in Section VI. Section VII presents the results of sensitivity analysis. Finally, concluding remarks are presented in Section VIII.

II. SOLAR ENERGY POTENTIAL IN TURKEY

Owing to its high potential, ease of use, and environment-friendly nature, solar energy in Turkey is capable of growing faster than other renewable energy sources. However, solar energy has some technological and economic difficulties, such as high installation costs, relatively low efficiency, and capacity factors, in comparison to other energy sources. With the solution of these barriers, power generation from solar photovoltaic (PV) panels will increase in Turkey in the near future. Turkey is geographically located in the Northern Hemisphere between 26°-45° east longitude and 36°-42° north latitude with a total surface area of 785,350 km^2 [18].

The Solar Energy Potential Atlas (GEPA) of Turkey created by The General Directorate of Energy Affairs (EIGM) is illustrated in Fig.1. Turkey's current geographical location is favorable for the utilization of solar energy generation from PVs. The energy potential produced from the sun is approximately 382 billion kWh in Turkey. According to the GEPA, depending on the geographical location of Turkey, daily total radiation intensity and sunshine duration are 4.17 kWh/m^2 and 7.58 hours, respectively. Besides, average annual total radiation intensity and annual total sunshine duration are 1521.7 kWh/m^2 and 2766.5 hours, respectively [19]. Turkey is divided into seven geographical regions: Black Sea, Aegean, Eastern Anatolia, Central Anatolia, South Eastern Anatolia, Mediterranean, and Marmara. The total annual potential of solar energy in terms of kWh/m^2/year for South Eastern Anatolia, Mediterranean, Eastern Anatolia, Central Anatolia, Aegean, Marmara and Black Sea Regions are 1460, 1390, 1365, 1314, 1304, 1168, and 1120, respectively [19].

According to the Global Solar Atlas published by the World Bank, regions with high solar energy potential are located between latitudes of 30° North and 30° South latitudes. However, the solar energy potential, which is quite high in these regions, cannot be transformed into the installed solar energy capacity and energy generation. Although Turkey is less advantageous in terms of solar radiation potential compared to those regions, it has higher solar radiation than China and many European countries, and therefore has a higher solar energy generation potential per square meter [20], [21], [22]. The total installed PV capacity in Turkey has reached 8 GW as of December 2021.

Government in Turkey has already developed a number of projects, plans, policies, and roadmaps to expand and encourage the utilization of solar energy in electricity production, such as feed-in tariffs, tax deductions, and national incentive systems.

III. WIND ENERGY POTENTIAL IN TURKEY

Diversifying energy sources, developing RES, and increasing the share of RES among alternative sources are important for Turkey's energy strategy. Wind energy is another promising alternative renewable energy source that reduces dependency on fossil fuels. Moreover, Turkey has a high wind energy potential owing to its geographical location.

The Wind Energy Potential Atlas (REPA) for Turkey created by The Ministry of Energy and Natural Resources (MENR) is shown in Fig.2. The REPA demonstrates the distribution of the wind speed intensity at a height of 100 m.

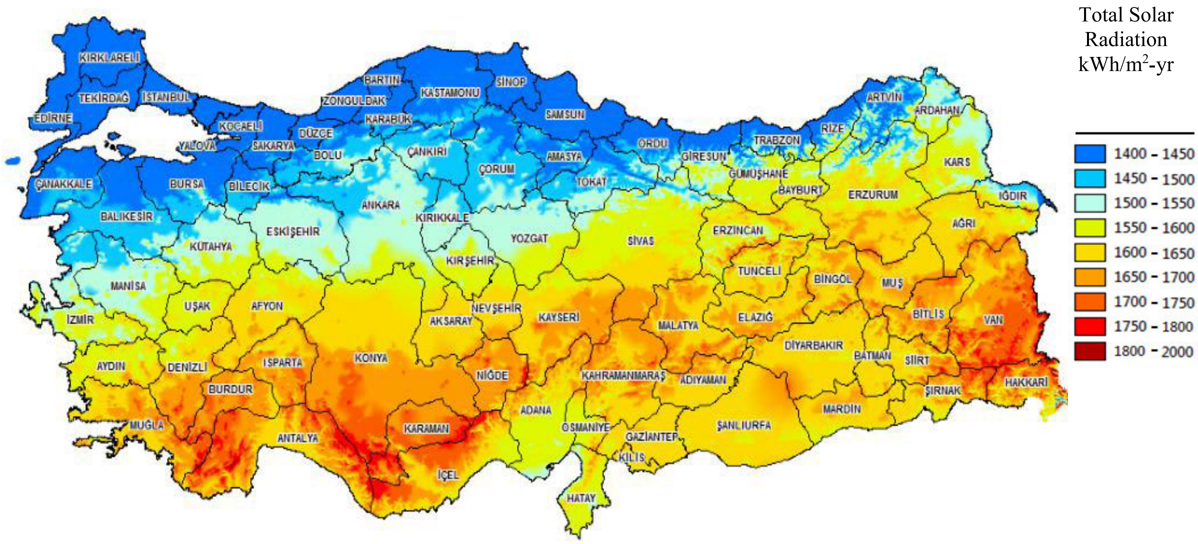


FIGURE 1. Solar energy potential atlas in turkey.

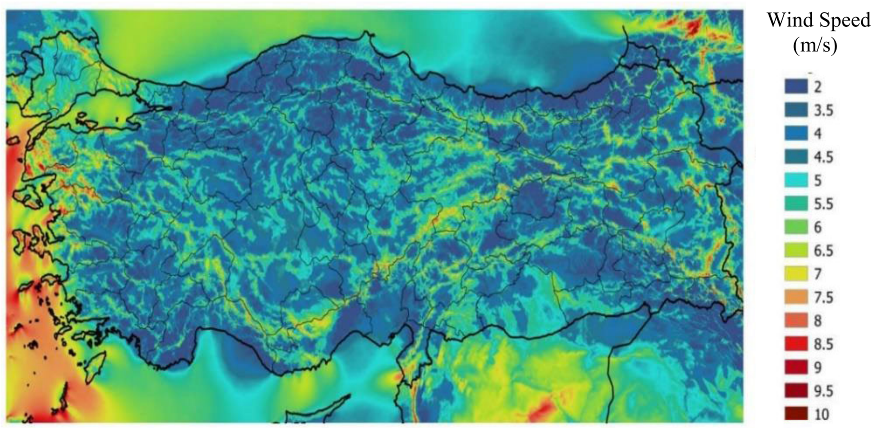


FIGURE 2. Wind energy potential atlas in turkey.

At the end of June 2022, the total installed wind-power capacity was 10,976 MW. In 2016, the cumulative capacity of wind energy was only 5,71 MW. The wind energy potential has considerably increased by approximately two times in the 6-year period between 2016-2022.

In addition, the share of wind energy in installed capacity has increased from 7.33% in 2016 to 10.81% in 2022 [23]. In Turkey, where the wind energy potential is increasing, approximately 20000 MW of wind power potential is targeted for 2025, and it is foreseen that 7% of the electricity needed will be provided from the wind energy source [24], [25].

It is clearly known that there is an imbalance between regions in the distribution of wind power plants in different countries and in Turkey, and the wind power density is higher in some areas. Climatic conditions, wind speed characteristics and the morphological structures of a land are more effective in the selection of the installation locations of wind power plants. It is concluded that wind energy, which exceeds the threshold of 10,000 MW in Turkey, is more concentrated in the Aegean and Marmara regions, as shown in Fig.2.

It is obvious that the wind speed is adequate for the installation of wind turbines on the Aegean, and Marmara coasts. Considering the distribution of wind power installed capacity in Turkey by 2021, the share of installed wind power capacity in Eastern Anatolia, South Eastern Anatolia, Black Sea, Central Anatolia, Mediterranean, Marmara, and Aegean are 0.16%, 1%, 3.80%, 9.90%, 12.04%, 35.36%, and 37.73%, respectively [24]. There is an electricity generation potential in all regions of Turkey for onshore wind energy from wind turbine (WT). In addition, offshore wind power plants have high potential for electricity generation because of the geographical structure of the Aegean and Marmara regions.

According to the MENR, it is predicted that energy demand will increase by an average of 7% per year until 2023 due to rapid population growth, urbanization, and modernization in Turkey. In this context, it is projected that the share of RES will gradually increase to meet the energy demand [26]. The Government of Turkey has set the target of increasing the share of renewables to 30%, increasing energy efficiency, decreasing greenhouse gas emissions, and increasing the installed capacity of solar power with wind power to 5,000 MW and 20,000 MW, respectively [27].

IV. RESEARCH BACKGROUND SYNOPSIS

According to reports published by the MENR in Turkey, electricity consumption in the building and service sectors accounts for approximately 49.9% of total electricity consumption [28]. In addition, there has been an increase in annual electricity consumption due to rapid population growth from the past to the present and the economic growth rates in Turkey. The share of the total residential electricity consumption in Turkey has changed over the years. In 1970, end-use electricity consumption by the residential sector in Turkey was 15.9% of the total end-use electricity consumption. The share of end-use electricity consumption in the residential sector increased from 15.9% to 21.1% in 2018 [29]. Considering the share of residential electricity consumption by sector, the effects of HRES on households were investigated in this study.

Several studies have been undertaken to design HRES to reduce household energy bills, decrease carbon emissions, and increase the share of renewables, energy efficiency, and generation power. The studies conducted in residential areas are summarized below.

In [30], the authors presented a stand-alone hybrid renewable energy system for 40 households to meet thermal and electrical loads. Simulations were performed to compare different systems using data collected with HOMER Software. The authors in [31] analyzed a hybrid PV/WT renewable energy system in Nigeria. They revealed that countries with similar economic and climatic conditions could benefit from the designed HRES. In [32], the effects of incentives for residential areas were determined using different HRES scenarios. The results showed that hybrid systems have a higher return on investment and a shorter payback period than PV and WT systems. The effects of 5 kW rooftop PV panels to meet the daily load of 11.27 kW of a household in different provinces of Turkey were investigated in [33]. The results obtained from simulations showed that incentives with feed-in tariff rates should be determined according to the diversity of solar radiation in different provinces. In [34], The authors designed and analyzed an islanded/grid-tied PV system in Ethiopia. The results demonstrated that net present cost (NPC) for grid-tied PV systems was approximately 12% lower than the utility grid tariff. In [35], a comparison of grid-tied PV systems for three different types of slab households was conducted. The results demonstrated that tariff regulation was more effective for middle-slab and low-slab households than for high-slab households. In [36], a techno-economic analysis of grid-tied solar PV systems was presented. According to the results, the integration of PV systems into apartments in Saudi Arabia has significant impacts on energy management. An off-grid hybrid microgrid composed of a PV/DG/BESS system was designed using HOMER software in [37]. In this study, which was carried out in Kilis, Turkey, the researchers revealed that solar radiation and climate data were sufficient to perform the analysis, and the system could be easily applied to other provinces when the same method was used for the analysis. Techno-economic analyses under stand-alone operation of hybrid systems were conducted in [38]. It was found that applying a demand response program to a microgrid reduced the total cost. The authors of [39] investigated the economic and environmental impacts of a HRES. The results indicated that the combination of wind energy and solar power significantly increased CO_2 emissions and energy costs. The economic feasibility of a grid-tied HRES was examined for three regions in the U.S. in [40]. The results showed that the most economical result occurred in regions with the highest amount of solar radiation. The researchers in [41] proposed a method for designing a HRES. According to the results, the proposed method and HOMER Pro software provide similar results in excess of electricity, energy cost, and energy produced. An analysis of islanded PV/WT systems for six UK sites was considered in [42]. The assessment demonstrated that the levelized cost of energy is affected by variations in the maintenance cost, equipment, and natural resources. The authors in [43] proposed a methodology for designing a HRES that considers different aspects. The results indicated that the proposed methodology has an impact on decision-making problems. A techno-economic analysis of HRES was performed in rural areas [44]. Stand-alone HRES, including PV/DG/BESS, met the energy demand of 200 kWh/d. The authors investigated the optimum scenario of a HRES to guarantee a reliable supply [45]. The results indicated that PV/DG/BESS was the optimal solution among the three scenarios suggested for off-grid systems. The aim of [46] was to determine the best hybrid system considering different scenarios. The findings showed that PV/WT was the optimum solution compared to PV-only and WT-only. Researchers designed a stand-alone PV/biomass system with a sensitivity analysis for the residential and agricultural sectors [47]. The results revealed that a HRES composed of a 10 kW PV array, a 12-kW convertor, an 8-kW biomass with 32 BESS supplied 137.49 kWh/d and 30.88 kWh/d load demand of agricultural and residential areas, respectively. In [48], a low-cost HRES was investigated to meet the energy demand for rural areas in South Africa. The results from the analysis demonstrated that a hybrid PV/micro hydro system met the load demand for off-grid systems during peak periods. The authors performed a study of islanded HRES to fulfill the domestic load demand in Pakistan [49]. The results indicated that PV/WT/BESS is the most viable and feasible solution, considering nine case studies. The aim of the authors was to obtain the most cost-effective and feasible solution to meet the domestic energy needs in [50]. The results showed that a HRES with a combination of PV/WT/BESS was the optimal solution. The authors in [51] conducted a study to investigate the potential of households' actual market performance. According to the results of the analysis carried out in different cities, a HRES composed of a 3-7 kW PV array satisfied energy needs depending on the solar radiation. Technical and economic assessments of on-grid HRES were discussed to determine the optimum system in [52]. The results of the analysis revealed that the combination comprising the PV/WT system yielded the lowest NPC and LCOE values of $337 and $0.002/kWh, respectively. The technical and economic feasibility of a grid-tied HRES was evaluated in [53]. PV systems have been found to be effective in reducing electricity bills and greenhouse gas (GHG) emissions. A study was conducted based on the sizing of the HRES [54]. The results obtained from the analysis indicated that the HRES consisting of a 21.1-kW PV, a 5-kW WT with 38 BESS met the energy demand. A stand-alone HRES, including PV/WT/biogas/BESS, was simulated to satisfy heat with energy demand in [55]. It was found that WT/biogas with BESS was the best configuration in the study area. A feasibility study was presented to determine the most efficient hybrid model at the seaside, sea level, and above sea level in [56]. According to the results, it was found that a HRES composed of PV/BESS at sea level was the optimal solution. A grid-tied HRES, including PV panels, was analyzed to meet a household demand of 14,887 kWh/d in [57]. It was shown that the hybrid system could reduce household energy bills. HOMER Pro software was used to design both grid-connected and stand-alone hybrid renewable systems based on household electricity consumption data, with the purpose of fulfilling domestic electricity requirements [58]. The findings showed that the grid-tied HRES was the most reasonable system for households compared with the stand-alone HRES. Feasibility and sensitivity analyses were discussed for residential loads in different areas [59]. The optimum solution was influenced by important parameters such as load demand, weather conditions, and different regions. To meet the energy needs of a building, a grid-connected photovoltaic energy system design was carried out using the electricity consumption data in [60]. It was determined that the costs of HRES could only be amortized for a maximum of 13 years. A feasibility study of a PV/DG/BESS hybrid energy system using three diverse strategies was presented in [61]. The findings showed that the combined dispatch strategy was the most optimal solution compared to the load-following and cycle-charging strategies. The analysis of stand-alone HRES, which is based on PV/WT/DG/BESS, was performed in different regions of Nigeria [62]. The results indicate that the best hybrid system by region was PV/WT/DG/BESS or PV/WT/BESS. The authors in [63] performed a feasibility analysis of a stand-alone HRES to find the optimal solution considering the lowest LCOE and NPC. It was observed that the PV/DG/BESS configuration was preferred for microgrid rollout. Simulation and optimization of a stand-alone HRES composed of PV/BESS considering three scenarios were presented for a rural house in [64]. The results of the analysis showed that the off-grid PV system satisfied the entire demand load. All the studies addressed in [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], and [64] for residential areas are summarized in Table 1. It should be noted that some of the studies reviewed above did not include any real residential data. In addition, some studies did not examine the selected region/regions, either on-grid or off-grid HRES. In this study, a techno-economic feasibility of a HRES was conducted in various provinces in seven regions of Turkey. HRES, both stand-alone and grid-tied, were compared from a techno-economic perspective for each province. In addition, real power data were collected using smart plugs and used to determine the residential load profile.

In addition to the studies referred to in [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], and [64], there are also studies in which artificial intelligence is included in the effective use of energy efficiency and renewable energy resources. A centralized energy management system (EMS) and machine learning models were employed to optimize the use of PV, DG, and BESS, with the goal of minimizing grid power injection and maximizing the usage of HRES [65]. The results showed that Regression Coarse Tree and Linear Regression methods give better results than other machine learning techniques in reducing peak demand and maximizing the utilization of HRES. In [66], a deep learning method based on short-term memory and discrete wavelet transformation was proposed to increase the utilization of HRES. The assessment demonstrated that the utilization of RES increased by approximately 60% and the energy imports drawn from the grid during peak time periods decreased by 98% with the proposed method. In [67], a review study was performed on studies involving deep learning methods in the literature to achieve significant improvements in power systems, including renewable energy systems. This study emphasizes that future studies on power systems, using deep learning, will have important effects on power systems, and the diversity of applications will increase. A novel taxonomy was used to assess the effectiveness of different deep-learning algorithms used in the field of solar and wind energy resources [68]. According to the results, the use of hybrid networks in deep learning techniques for renewable energy is recommended, as these networks demonstrate superior performance compared to single networks. A deep learning approach was used to propose four predictive models as Fully Recurrent Neural Networks -1,-2,-3 (FRNN), and Time Lagged Recurrent Networks (TLRN) based on RNN and TLRN for forecasting the performance of PV current considering a photovoltaic plant with a capacity of

TABLE 1. Summary of the studies for residential area in the literature.

References	Years	Country	Construction	System Configuration	Domestic Energy Demand	Various Locations	Detailed Load Profile	Sensitivity Analysis
[30]	2020	Turkey	PV/WT/DG/BESS	Islanded	320 kWh/d	No	No	Yes
[31]	2020	Nigeria	PV/WT/BESS	Islanded	5.58 kWh/d	No	No	No
[32]	2017	Turkey	Grid/PV/BESS Grid/WT/BESS Grid/PV/WT/BESS	Grid-tied	11.3 kWh/d	No	No	No
[33]	2020	Turkey	Grid/PV	Grid-tied	11.27 kWh/d	Yes	No	Yes
[34]	2021	Ethiopia	Grid/PV PV/BESS	Grid-tied Islanded	324 kWh/d	No	No	Yes
[35]	2017	India	Grid/PV/BESS	Grid-tied	5.7 kWh/d 11 kWh/d 22 kWh/d	No	No	No
[36]	2019	Saudi Arabia	Grid/PV	Grid-tied	average 74.48 kWh/d	No	No	Yes
[37]	2017	Turkey	PV/DG/BESS	Islanded	10 kWh/d	No	Yes (shown in Table)	No
[38]	2017	Iran	PV/WT/BESS	Islanded	51.84 kWh/d	No	Yes (shown in Table)	No
[39]	2018	Yemen	DG-only WT/DG/BESS PV/DG/BESS PV/WT/BESS PV/WT/DG/BESS	Islanded	886 kWh/d	No	Yes (shown in Table)	Yes
[40]	2018	USA	Grid/PV/BESS	Grid-tied	8,765 kWh 13,750 kWh 7,887 kWh	Yes	No	Yes
[41]	2016	Morocco	PV/WT/BESS	Islanded	18.7 kWh/d	No	Yes (obtained from algorithm)	Yes
[42]	2018	UK	PV/WT	Islanded	3,902 kWh/yr	Yes	Yes (estimated)	Yes
[43]	2015	Venezuela	PV/WT/DG/BESS	Islanded	average 11 kWh/d	No	No	No
[44]	2013	Iran	PV/DG/BESS	Islanded	200 kWh/d	No	No	No
[45]	2017	Cambodia	DG-only PV/DG PV/DG/BESS	Islanded	14.364 kWh/d	No	No	Yes
[46]	2022	Malaysia	Grid/PV/DG/BESS Grid/WT/PV/DG/BESS	Grid-tied	11.26 kwh/d	Yes	No	Yes
[47]	2017	Pakistan	PV/DG/BESS	Islanded	30.882 kWh/d	No	Yes (shown in Table)	Yes
[48]	2009	South Africa	PV/micro hydro/DG/BESS	Islanded	16 kWh/d	No	No	No
[49]	2019	Pakistan	PV/WT/DG/BESS	Islanded	7.19 kWh/d	No	Yes (shown in Table)	No
[50]	2019	Pakistan	WT/DG/BESS WT/BESS DG DG-/BESS WT/DG	Islanded	11.25 kWh/d	No	No	No
[51]	2020	China	Grid/PV/BESS	Grid-tied	6.67 kWh - 13.33 kWh/d	Yes	No	No
[52]	2023	Republic of Djibouti	Grid/PV/WT	Grid-tied	43 kWh/d	No	Yes (shown in Table)	Yes
[53]	2012	Australia	Grid/PV/BESS	Grid-tied	23 kWh/d	Yes	No	Yes
[54]	2020	Pakistan	PV/WT/DG/BESS	Islanded	35.94 kWh/d	No	Yes (shown in Table)	Yes
[55]	2020	UK	Grid/Biogas/PV/WT/BESS	Grid-tied	4.6 kWh/d + heat consumption	No	Yes	Yes

TABLE 1. ***(Continued.)*** **Summary of the studies for residential area in the literature.**

[56]	2020	Philippines	PV/WT/BESS	Islanded	11 kWh/d	No	No	No
[57]	2020	Bangladesh	Grid/PV	Grid-tied	14,887 kWh/d	No	No	No
[58]	2021	Turkey	PV/DG/BESS Grid/PV	Grid-tied Islanded	4.13 kWh/d	No	No	No
[59]	2019	Bangladesh	Grid/WT/PV/BESS WT/PV/BESS	Grid-tied Islanded	2,687.54 kWh/d 1,521.37 kWh/d	Yes	Yes (shown in Table)	Yes
[60]	2022	Turkey	Grid/PV/BESS	Grid-tied	18 kWh/d	No	No	No
[61]	2019	Iraq	PV/DG/BESS	Islanded	145 kWh/d	No	No	Yes
[62]	2018	Nigeria	PV/WT/DG/BESS	Islanded	7.23 kWh/d	Yes	Yes (from reference)	No
[63]	2022	Republic of Namibia	PV/DG/BESS	Islanded	2.71 kWh/d	No	Yes (shown in Table)	Yes
[64]	2021	Libya	PV/BESS PV/DG/BESS	Islanded	9.6 kWh/d	No	Yes (shown in Table)	No

1.4 kW in [69]. The results showed that FRNN-2 and FRNN-3 demonstrated the best performance among the prediction models because they exhibited lower MSE values, indicating a better fit to the experimental data. In [70], an AI-based energy management system was proposed for urban buildings with PV and BESS systems. This study demonstrated that the proposed solution could reduce the electricity bill by 55%. A learning model was developed using a strategy derived from a set of users to model the demand response of residential consumers considering renewable energy [71]. The results showed that the learning paradigm could generate predicted demand response profiles with a maximum accuracy of 80%.

Various R&D studies have been conducted on renewable energy as well. In the last ten years, there has been a remarkable increase in the efficiency of solar cells. Solar cells have achieved remarkable feat by increasing their average conversion efficiency from 15% to more than 20%. Furthermore, employing a solar panel system that tracks the movement of the sun along a single axis can lead to significant improvements in performance, with gains ranging from 25% to 35% [72]. In 2016, researchers developed a solar cell utilizing perovskite crystals that can yield up to 20% higher efficiency than conventional silicon-based solar cells. In addition, in 2022, they were able to fabricate initial perovskite solar cells that were commercially feasible, with the ability to be produced at room temperature and requiring less energy to manufacture compared to solar cells based on silicon [73], [74]. The inability of solar panels to collect sunlight at night is a drawback of using solar energy. However, researchers have developed a solar power plant that overcomes this challenge by storing the energy generated by sunlight during the day in a battery system, allowing electricity to be produced at night. Additionally, using a thermoelectric generator, researchers have devised PV panels capable of generating electricity at night as well [75]. The growth in wind power capacity has led to a notable increase in the need for energy storage systems [76]. To facilitate the integration of wind and other renewable sources, various new solutions, including hybridization, are being increasingly adopted in emerging markets [77]. A new development in the field of materials for wind turbine blades is the utilization of natural fibers [78]. These fibers are being employed as substitutes for glass and carbon fibers, as they are more readily available, less expensive, and have a lower environmental impact than synthetic fibers.

The studies summarized above provide a strong foundation for this study. However, a techno-economic comparative study of grid-tied and stand-alone HRES has not been properly addressed in the literature for residential areas located in Turkey. This study focuses on the economic, technical, and environmental performance of grid-tied and stand-alone HRES in 21 provinces of Turkey under different climate conditions. This study fills a much-needed research gap. In addition, this study presents a realistic domestic load profile for a family of 4 for simulations. Even though real-time data on residential areas are not available in most studies in the literature, real data sets will be used in this study, which results in an increase in the accuracy of the techno-economic analysis. Furthermore, to the best of our knowledge, no prior comparative studies have investigated more than 20 provinces for both grid-connected and off-grid HRES considering the residential sector and there has been no study that reviews the recent studies in the field of HRES for residential sector in the literature. This research would be to offer guidance to engineers and researchers.

V. INPUT PARAMETERS OF THE SYSTEM

A. RESIDENTIAL LOAD PROFILE

Electricity consumption in residential areas is affected by many factors, such as the number of electrical appliances, hours of usage, number of occupants, living habits, geographical location of households, weather conditions, and level of people's wealth. Accurately determining the load profile and total electricity consumption is of great importance for the analysis of HRES. To determine a realistic and accurate load profile, the electricity consumption of household electrical appliances was measured using smart plugs. The average size of the selected dwelling for a family of four is approximately 180 m^2. The electricity consumption of some electrical appliances used in this household, where four people live, is shown in Figures to 3-12. Furthermore,

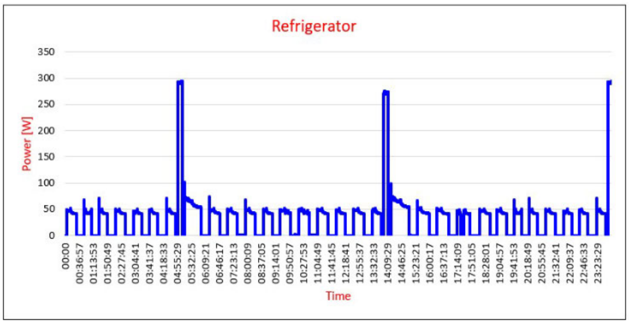


FIGURE 3. The power consumption of refrigerator.

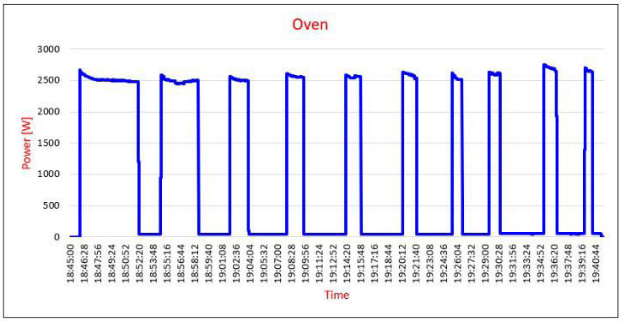


FIGURE 4. The power consumption of oven.

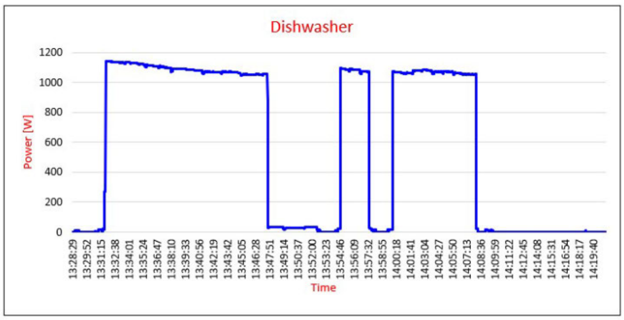


FIGURE 5. The power consumption of dishwasher.

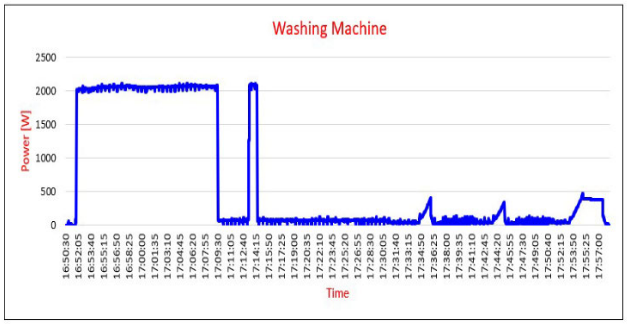


FIGURE 6. The power consumption of washing machine.

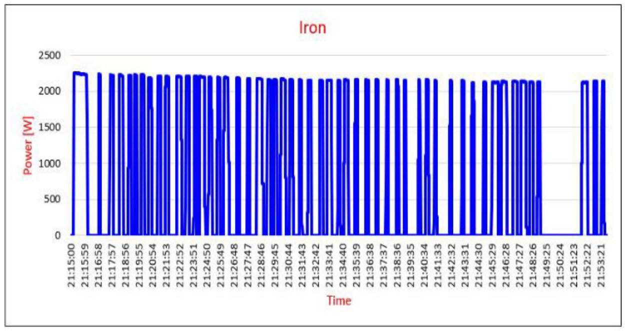


FIGURE 7. The power consumption of iron.

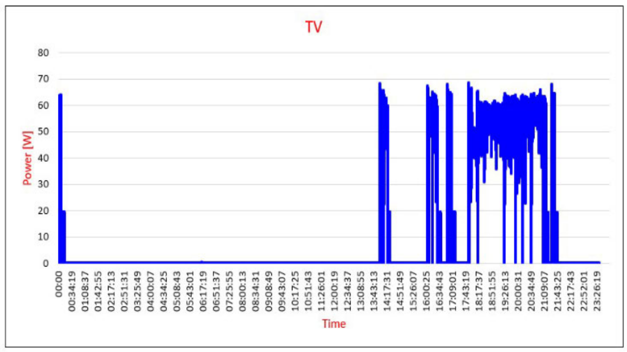


FIGURE 8. The power consumption of TV.

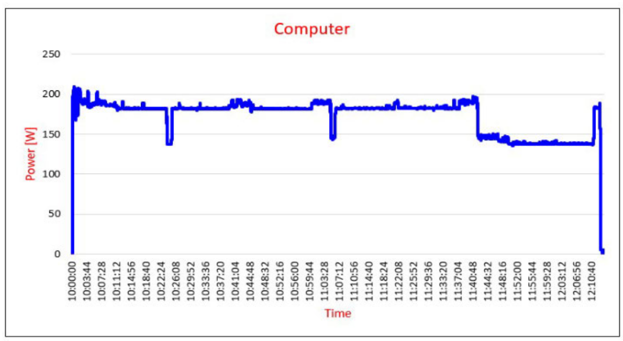
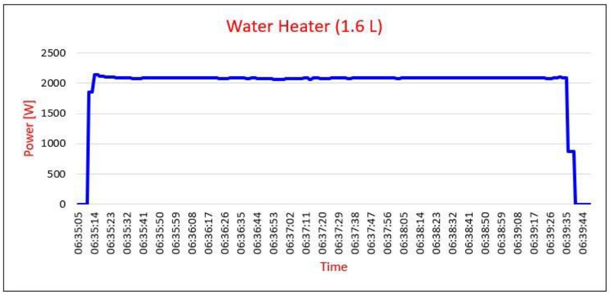


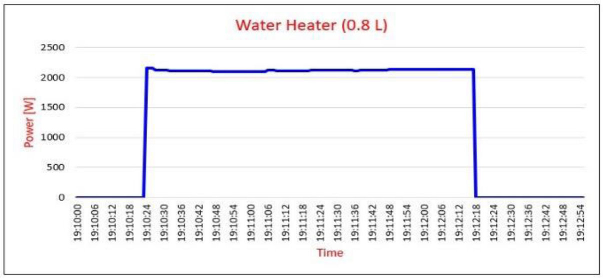
FIGURE 9. The power consumption of computer.

considering the number of hours of operation of the electrical devices of the occupants, the daily average load profile on an hourly basis is displayed in Fig.13.

The peak load demand occurred from 19:00 to 20:00. When the load profile was examined, the energy consumption tended to be highest during the evening. Due to the fact that family members are return home and start using their electrical appliances in the evening. Similarly, because family members go to school or work at 08:00-16:00, the load demand in these hours is lower than that in the evening hours. According to the Regulation on Electric Power Installations in Turkey, simultaneity (demand) coefficients should be considered in the creation of the residential load profile [79]. For this reason, to create more realistic load data in the HOMER Software, parameters of day-to-day and timestep as random variability were taken as 15% and 20%, respectively [80], [81]. In light of this information, for a family of four, the average daily electricity consumption and



(a)



(b)

FIGURE 10. The power consumption of water heater (a) 1.6 L (b) 0.8 L.

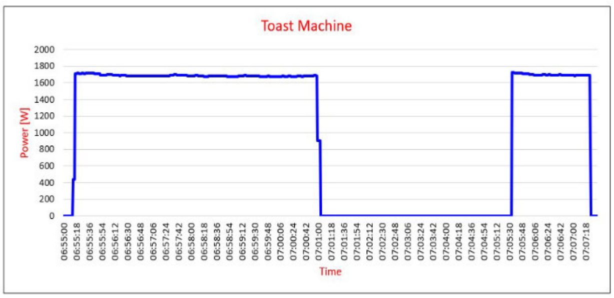


FIGURE 11. The power consumption of toast machine.

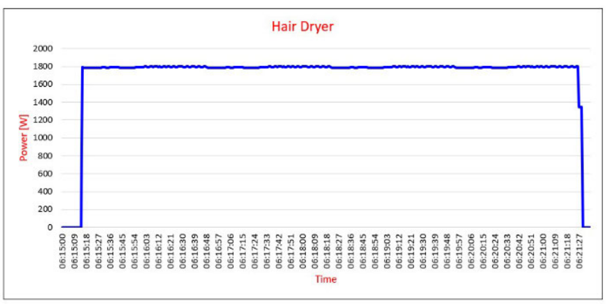


FIGURE 12. The power consumption of hair dryer.

demand were measured as 13.26 kWh and 6.20 kW, respectively. Fig.3 shows the power consumption of a refrigerator that constantly runs for 24 h a day. The refrigerator consumed an average of 778.055 W of power per day. Fig.4 displays the power consumption of an oven at 180°C for cooking and baking. Operating the oven for 56 minutes between 18:45-19:41, lead to 938.39-W power consumption. Fig.5 and

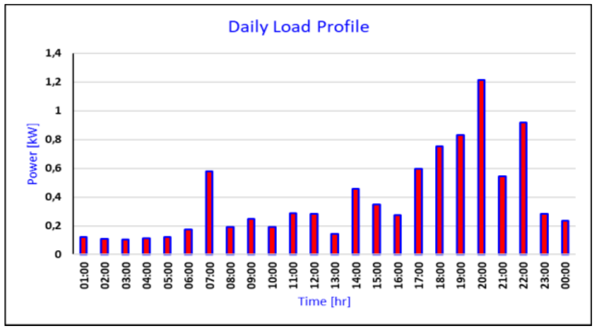


FIGURE 13. The daily load profile for HRES.

Fig.6 show the power consumption of a dishwasher and a washing machine, respectively. The washing machine was operated between 16:50-17:58 and 20:45-21:45, while the dishwasher operated between 13:28-14:20 and 19:00-20:16. A dishwasher operated at 65°C and a washing machine operated at 40°C consumed a total of 812.80 W and 995.73 W, respectively. When the temperature level of 2 was adjusted for an iron between 21:15-21:53, the power consumption was measured as 492.27 W (Fig.7). Fig.8 shows an average of 266.89 W power consumption of a TV, which operated for 24 h, including the standby mode. When the computer was run three times a day between 10:00-12:13, 15:07-19:35, and 20:30-22:53, the total power consumption was measured as 1536.88 W (Fig.9). When the toast machine was operated in the morning between 06:55-07:07 and 08:55-09:08, it resulted in a total of 429.21 W power consumption (Fig.11). Power consumption measured for boiling 1.6 L water at hours between 06:35-06:39 and 0.8 L water at hours between 19:10-19:12 in a water heater was 154.49 W and 67.15 W, respectively as seen in Fig.10. A hair dryer with a medium-speed mode was operated between 06:15-06:21 and had a power consumption of 211.76 W (Fig.12). Additionally, in the determination of the load profile, a combi boiler and a freezer operated for 24 h and 10 bulbs rated 6 W each used between 17:30-00:00 were included. The combi boiler, freezer, and bulbs consumed an average of 712.34 W, 499.21 W, and 390 W, respectively. Dishwasher, washing machine, computer, and toast machine operate more than once a day. Fig.5, Fig.6, Fig.9, and Fig.11 show the power consumption of the dishwasher, washing machine, computer, and toast machine, respectively, when operated once.

B. SYSTEM INPUTS

In this section, the features of each component used in a HRES are explained. The grid-connected HRES has four important components: the grid, WT, converter, and PV. Similarly, a stand-alone HRES consists of a WT, DG, converter, PV, and BESS. A schematic design of the grid-tied and stand-alone HRES is shown in Fig.14 and Fig.15, respectively.

In the proposed HRES system, the costs of the components and technical parameters are obtained either as a result of bilateral negotiations or through a tender offer. All components used in the system are available in the Turkish market. To obtain more precise, consistent, and accurate results using HOMER Pro, the costs of the components and technical parameters are very important. In this way, the HOMER software finds the optimal sizes for the system components considering capacity [61]. The technical and cost data of the PV, WT, DG, converter, and BESS are shown in Tables 2-6, respectively. In addition to the economic parameters of the components, data on the interest rate, inflation, real interest rate, and project life are required for the proposed system. The project's life was taken as 25 years. Considering the data of the Central Bank of the Republic of Turkey for the last 10 years, the interest rate was 8%, and the inflation rate was 10%. The real interest rate was found to be -1.82% [82].

The capital and replacement costs of flat-plate photovoltaic (PV) modules, which have a nominal capacity of 350 W and a 25-year warranty for HRES, are determined as 574.52 \$/kW. A wind turbine (WT) of 2 kW power rating with a height of 12 m from is selected for this study. The capital and replacement cost are \$1,904.16 and \$1,600.00, respectively. The hub height can be increased depending on the location of the region, which increases capital cost. A diesel generator (DG), which is used as an alternative energy source and preferred backup power when there is no access to the grid or temporary faults in the distribution of electricity, is added as a component for the off-grid HRES, as shown in Fig.15 [83].

The capital and replacement costs of the diesel generator, which has an operating life of 15,000 h, are \$362.10. Inverter with a nominal capacity of 3 kW or 4 kW, which is used in both on-grid and off-grid systems and regulate the power flow between AC-DC, is selected in this research. Capital cost of an inverter with 90% efficiency and a 10-year warranty for 3 kW and 4 kW are \$1,248.51 and \$1,375.55, respectively. BESS, which is used to provide energy continuity in the HRES, is utilized to support the PV as storage units.

24-V Li-ion battery with a 2.5 kWh energy storage capability is selected in this study. Li-ion batteries are chosen because of their higher capacity and longer life compared to lead-acid batteries [84], [85].

The replacement and capital costs of the BESS were taken as \$595.85. Moreover, selling and buying of electricity to and from the grid are 0.074 \$/kWh and 0.106 \$/kWh for grid-tied HRES, respectively.

TABLE 2. Technical and cost data of PV system.

Parameter	Specification
Rated capacity	350 W
Maximum number of units	15
Panel type	Flat plate
System dimensions	1700mm x 1016mm x 40mm
Nominal efficiency	18.1%
Derating factor	80%
Capital cost	574.52 \$/kW
Replacement cost	574.52 \$/kW
O & M cost	10 \$/kW/yr
Lifetime	25 years

TABLE 3. Technical and cost data of WT.

Parameter	Specification
Rated power	1.8 kW
Hub height	12 m
Capital cost/unit	1,904.16 \$
Replacement cost/unit	1,600.00 \$
O & M cost/unit	300 \$/kW/yr
Lifetime	20 years

TABLE 4. Technical and cost data of DG.

Parameter	Specification
Capacity	8 kW
System dimensions	680mm x 455mm x 545mm
Capital cost	362.10 \$/kW
Replacement cost	362.10 \$/kW
O & M cost	0.03 \$/op. hour
Fuel Price	1.42-1.45 \$/L
Lifetime	15,000.00 hours

C. SELECTED PROVINCES AND CLIMATIC DATA

The solar and wind energy potential in Turkey are described in Sections II and III, respectively. It is clear that the potential for electricity generation from solar energy is higher than the potential for electricity generation from wind energy. In light of this information, 21 provinces were selected by considering the highest, median, and lowest solar radiation in seven regions of Turkey. Wind turbines are also included in the proposed HRES because the Aegean and Marmara regions of Turkey have higher wind potential. The geographical coordinates of the selected provinces according to the lowest, median, and highest solar radiation and the characteristics of the region where they are located are shown in Table 7. Furthermore, the solar radiation, wind speed, sunshine duration, and temperature data of the 21 provinces are compared in Fig. 16. Data on sunshine duration were obtained from [86]. According to Fig.16, solar radiation data varies from 3.6 kWh/m^2/day to 5.1 kWh/m^2/day. Among the 21 provinces, the province with the lowest solar radiation is Artvin in the Black Sea region, whereas the province with the highest solar radiation is Aydın in the Aegean region. In addition, Artvin in the Black Sea region has a minimum wind speed of 2.56 m/s, whereas Çanakkale in the Marmara region has a maximum wind speed of 6.83 m/s. The temperature

TABLE 5. Technical and cost data of converter.

Parameter	Specification
Capacity	3 kW, 4kW
System dimensions	435mm x 470mm x 176mm
Capital cost	1,248.51 $ for 3kW 1,375.55 $ for 4kW
Replacement cost	1,148.51 $ for 3kW 1,375.55 $ for 4kW
O & M cost	20 $/yr
Efficiency	90%
Lifetime	10 years

TABLE 6. Technical and cost data of BESS.

Parameter	Specification
Nominal voltage	24 V
Battery capacity	100 ah
Nominal capacity	2.5 kWh
Battery type	Li-ion
System dimensions	30cm x 50cm x 40cm
Capital cost	595.85 $
Replacement cost	595.85 $
O & M cost	8 $/yr
Cycle life	2500 cycle

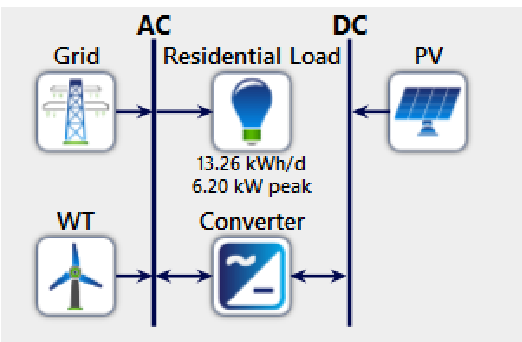


FIGURE 14. The proposed grid-tied Grid/WT/PV scheme.

values are quite variable throughout the country varying from 3.79°C to 19.74°C.

D. ECONOMIC AND ENVIRONMENTAL METRICS

The Net Present Cost (NPC) and Cost of Energy (COE) were used as primary parameters to find the optimum solution in many studies [87], [88], [89], [90]. In addition to these parameters, the renewable fraction (RF) and quantity of emissions were considered in this study. NPC is the sum of all revenues and costs over the lifetime of the project. NPC is calculated

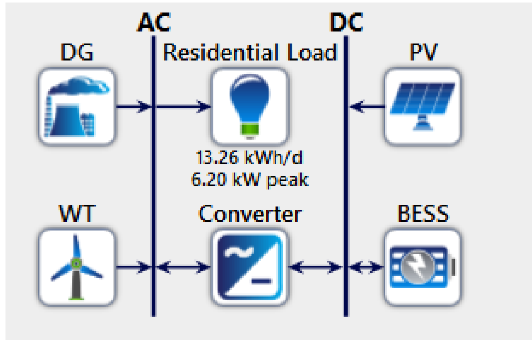


FIGURE 15. The proposed stand-alone WT/PV/DG/BESS scheme.

as following (1):

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

where $C_{an,total}$ is the total annualized cost ($/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.

COE is the ratio of the annualized cost of producing electricity to the total electric load served and is described as following (2) and (3):

$$COE = \frac{C_{an,total}}{E_{served}} \tag{2}$$

$$COE = \frac{C_{an,total}}{AC_{Load} + DC_{Load}} \tag{3}$$

where E_{served} shows the total electrical load served in terms of kWh/yr. Similarly, AC_{Load} and DC_{Load} indicate the AC and DC primary loads, respectively.

RF, which is expressed as the fraction of the energy delivered to the load that originates from renewable power sources, is calculated using equation (4):

$$RF = 1 - \frac{E_{nonren}}{E_{served}} \tag{4}$$

where E_{nonren} is the nonrenewable electrical production in terms of kWh/yr.

The HOMER program uses the annual real interest rate when performing cost calculations. The annual real interest rate is determined using the following formula (5):

$$i = \frac{i' - f}{1 + f} \tag{5}$$

where, i is the annual real interest rate. i' and f denote the nominal interest rate and the annual inflation rate, respectively.

VI. SIMULATION RESULTS AND DISCUSSIONS

In this study, grid-tied and stand-alone HRES were designed to meet the residential load demand. A total of 21 provinces, three from each of the seven regions of Turkey with different geographical features where HRES systems were implemented, were selected. Considering the size of the system components in each province, it is aimed to determine the

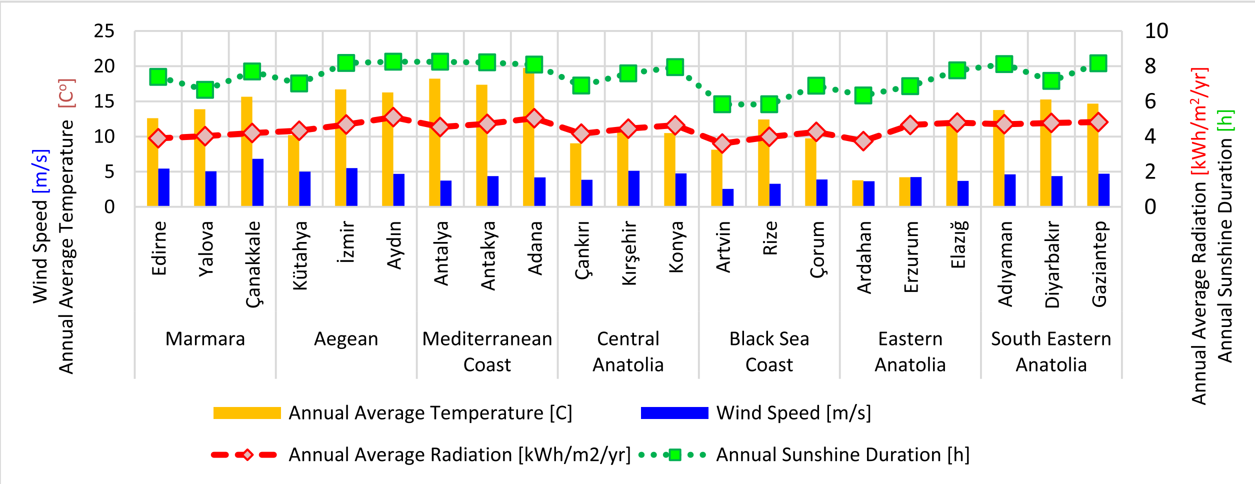


FIGURE 16. Comparison of climate data by provinces.

TABLE 7. Geographical coordinates of selected provinces.

Regions	Name of Province	Situation of Solar Radiation	Solar Radiation [kwh/m²/day]	Temperature [°C]	Wind Speed [m/s]	Latitude	Longitude	Altitude	Climatic Regions
Marmara	Edirne	Lowest	3.9	12.61	5.43	41° 40.6'N	26° 33.3'E	42 m	warm to hot dry summers cool to cold wet winters
	Yalova	Median	4.02	13.87	5.06	40° 39.3'N	29° 17.1'E	7 m	
	Çanakkale	Highest	4.2	15.65	6.83	40° 8.8'N	26° 24.5'E	12 m	
Aegean	Kütahya	Lowest	4.33	10.19	5.01	39° 25.2'N	29° 59.1'E	950 m	hot, dry summers mild to cool wet winters
	İzmir	Median	4.68	16.69	5.5	38° 25.4'N	27° 8.6'E	10 m	
	Aydın	Highest	5.1	16.26	4.68	37° 50.3'N	27° 50.7'E	64 m	
Mediterranean Coast	Antalya	Lowest	4.54	18.23	3.73	36° 53.8'N	30° 42.8'E	39 m	hot, dry summers mild to cool wet winters
	Antakya	Median	4.72	17.35	4.37	36° 12.1'N	36° 9.7'E	85 m	
	Adana	Highest	5.04	19.74	4.18	36° 59.5'N	35° 19.8'E	23 m	
Central Anatolia	Çankırı	Lowest	4.16	9.04	3.85	40° 36.0'N	33° 37.0'E	723 m	hot, dry summers cold, harsh winters
	Kırşehir	Median	4.45	10.62	5.12	39° 8.8'N	34° 9.6'E	978 m	
	Konya	Highest	4.64	10.48	4.76	37° 52.5'N	32° 29.6'E	1016 m	
Black Sea Coast	Artvin	Lowest	3.6	8.12	2.56	41° 10.9'N	41° 49.2'E	520 m	warm, wet summers cool to cold wet winters
	Rize	Median	3.98	12.42	3.29	41° 1.5'N	40° 31.1'E	10 m	
	Çorum	Highest	4.26	9.75	3.9	40° 33.0'N	34° 57.2'E	801 m	
Eastern Anatolia	Ardahan	Lowest	3.74	3.79	3.64	41° 6.8'N	42° 8.2'E	1870 m	hot, dry summers cold, harsh winters
	Erzurum	Median	4.66	4.22	4.24	39° 54.3'N	41° 15.9'E	1890 m	
	Elazığ	Highest	4.79	11.7	3.68	38° 40.5'N	39° 13.4'E	1067 m	
South Eastern Anatolia	Adıyaman	Lowest	4.7	13.77	4.63	37° 45.8'N	38° 16.6'E	669 m	hot, dry summers cold, harsh winters
	Diyarbakır	Median	4.77	15.26	4.37	37° 55.5'N	40° 12.7'E	670 m	
	Gaziantep	Highest	4.82	14.67	4.71	37° 4.0'N	37° 22.7'E	843 m	

optimal solution. In addition, the optimal solutions for each province were compared. The effects of geographic features were investigated to obtain the optimum solutions for each province. Sensitivity analyses for the examination of NPC, COE, RF, and emissions were also conducted using HOMER Software. To evaluate the consequences of uncertainty or changes in the model inputs, HOMER runs numerous optimizations under a given set of input assumptions for the sensitivity analysis. A flowchart of the major steps performed for the research methodology adapted from [91] is presented in Fig.17.

Considering the local PV market in Turkey, there are two types of PV modules: monocrystalline and polycrystalline. These modules are composed of either 60 or 72 PV cells, which are generally connected in series with a peak power ranging from 200 to 460 W_p. The PV system in this study has

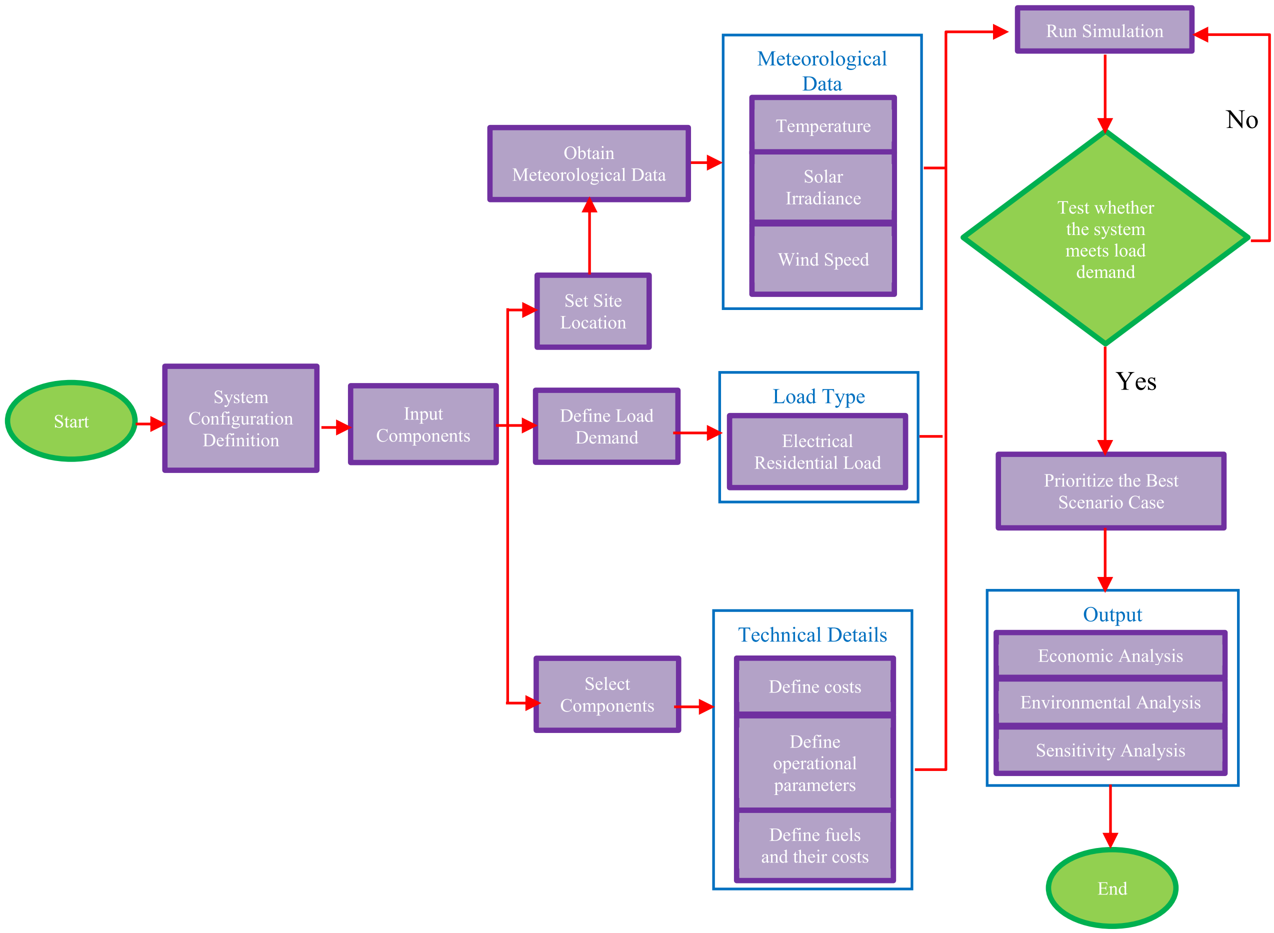


FIGURE 17. Flowchart of the research study.

a capacity of 5 kW_p and is made up of one string comprising 15 monocrystalline PV modules connected in a series configuration. Each module is composed of 60 cells connected in series and has a power rating of 350 W_p. As most households do not exceed the annual production of a 5 kW_p PV generator, the upper limit in the HOMER software for PV panels was selected as 5 kW_p [92]. Studies using 5-kW rooftop PV panels are available in the literature [33], [93], [94], [95]. In addition, grid usage was limited because of the increasing renewable energy usage and decreasing CO_2 emissions for grid-tied HRES [96]. Important parameters such as NPC, COE, RF, and amount of CO_2 were considered in the evaluation of the optimum system configuration for each province to meet the residential load demand.

The techno-economic, environmental, and emission evaluations of the optimized HRES for each province are shown in Table 8. Table 8 shows the optimum grid-tied and stand-alone HRES configurations and HOMER's main outputs as NPC, COE, and RF with the amount of CO_2 according to each feasible solution. The main results of this study as follows:

- The optimum system configuration for a grid-tied HRES was provided by Grid/PV/WT for many provinces.
- Since the wind speed is quite low in Antalya, Artvin, Rize and Elazığ compared to other provinces, wind turbines are not recommended for the optimum solution of grid-connected HRES.
- Considering the geographical features shown in Table 7, wind turbines were not included in the grid-connected HRES systems for provinces with a wind speed of less than 3.8 m/s.
- Because WTs are not included in these provinces, NPC, COE, and the amount of CO_2 in the system have the highest values compared to other provinces.
- Considering the stand-alone optimum system configuration, it is seen that the optimum solution is PV/WT/DG/BESS for all provinces. Because there is no grid support in off-grid HRES, wind turbines are included in the system even in provinces with low wind speeds to meet the required load.
- The NPC varies between \$2,504.00 – \$8,951.00 and \$23,372.00 – \$40,858.00 for grid-tied and stand-alone HRES, respectively. The fluctuation is closely related to the wind speed and solar irradiation at the geographic location of the provinces.

TABLE 8. Optimization results for grid-tied and stand-alone HRES.

Provinces	Off-grid								On-grid						
	PV (kW)	WT (kW)	DG (kW)	BESS (kWh)	NPC ($)	COE ($/kWh)	RF (%)	CO_2 (kg/yr)	PV (kW)	WT (kW)	Converter (kW)	NPC ($)	COE ($/kWh)	RF (%)	CO_2 (kg/yr)
Edirne	4.90	1.80	6.90	27.6	26,107.00	0.221	96.30	210	5.00	1.80	3	4,805.00	0.020	84.10	1,252
Yalova	3.10	3.60	6.90	25.1	27,234.00	0.231	96.80	182	5.00	1.80	3	5,399.00	0.023	82.80	1,300
Çanakkale	3.76	1.80	6.90	22.6	23,372.00	0.198	96.00	228	5.00	1.80	3	2,504.00	0.010	87.40	1,041
Kütahya	4.70	1.80	6.90	27.4	26,535.00	0.225	95.70	244	5.00	1.80	4	4,688.00	0.019	83.80	1,268
İzmir	4.05	1.80	6.90	27.6	25,135.00	0.213	96.50	201	5.00	1.80	3	3,303.00	0.013	85.60	1,165
Aydın	4.80	1.80	6.90	27.6	26,001.00	0.220	96.30	209	5.00	1.80	4	3,932.00	0.015	84.20	1,184
Antalya	5.00	1.80	6.90	32.7	29,237.00	0.248	95.30	267	5.00	-	3	7,323.00	0.039	66.40	2,026
Antakya	4.89	1.80	6.90	30.1	28,214.00	0.239	95.20	272	5.00	1.80	3	5,725.00	0.024	80.90	1,452
Adana	4.32	1.80	6.90	31.7	27,348.00	0.232	96.50	198	5.00	1.80	4	5,472.00	0.022	81.40	1,411
Çankırı	4.96	3.60	6.90	27.6	31,287.00	0.265	95.50	254	5.00	1.80	4	7,530.00	0.034	78.00	1,518
Kırşehir	4.76	1.80	6.90	27.6	26,521.00	0.225	95.70	241	5.00	1.80	4	4,222.00	0.017	84.00	1,258
Konya	4.23	1.80	6.90	30.1	26,757.00	0.227	96.00	224	5.00	1.80	4	4,511.00	0.018	83.50	1,272
Artvin	5.00	3.60	6.90	40.2	40,858.00	0.346	91.20	503	5.00	-	3	8,951.00	0.051	60.70	2,122
Rize	4.99	3.60	6.90	32.7	33,571.00	0.284	95.30	267	5.00	-	3	8,251.00	0.046	63.00	2,089
Çorum	4.94	3.60	6.90	27.6	30,659.00	0.260	96.10	220	5.00	1.80	4	7,172.00	0.031	78.50	1,512
Ardahan	4.82	3.60	6.90	30.1	33,098.00	0.280	94.60	304	5.00	-	3	8,473.00	0.048	62.30	2,104
Erzurum	4.77	1.80	6.90	32.7	28,651.00	0.243	95.70	246	5.00	1.80	4	5,432.00	0.022	81.10	1,432
Elazığ	4.83	1.80	6.90	35.2	31,466.00	0.267	94.00	341	5.00	-	4	6,539.00	0.032	68.30	1,976
Adıyaman	4.05	1.80	6.90	30.1	28,022.00	0.237	94.70	303	5.00	1.80	4	5,034.00	0.020	82.30	1,370
Diyarbakır	4.74	1.80	6.90	32.7	28,803.00	0.244	95.50	254	5.00	1.80	4	5,454.00	0.022	81.30	1,422
Gaziantep	4.84	1.80	6.90	30.1	28,366.00	0.240	95.00	281	5.00	1.80	4	4,763.00	0.019	82.60	1,367

- Among the 21 provinces, Çanakkale has the lowest NPC, whereas Artvin has the highest NPC for off-grid and on-grid HRES from an economic perspective.
- PV systems produce higher CO_2 than PV/WT configurations for grid-tied HRES.
- When comparing provinces in seven regions, the lowest NPC was obtained in Çanakkale (Marmara) followed by İzmir (Aegean), Kırşehir (Central Anatolia), Adana (Mediterranean Coast), Adıyaman (South Eastern Anatolia), Erzurum (Eastern Anatolia), and Çorum (Black Sea Region) at a NPC of $23,372.00, $25,135.00, $26,521.00, $27,348.00, $28,022.00, $28,651.00, and $30,659.00, respectively, for stand-alone HRES including PV/WT/DG/BESS. Considering the NPC, it is clearly shown that the winning province is Çanakkale in Marmara Region. Similarly, the highest NPC was found in Artvin (Black Sea Region), followed by Ardahan (Eastern Anatolia), Çankırı(Central Anatolia), Antalya (Mediterranean Coast), Diyarbakır (South Eastern Anatolia), Yalova (Marmara), and Kütahya (Aegean) at a NPC of $40,858.00, $33,098.00, $31,287.00, $29,237.00, $28,803.00, $27,234.00, and $26,535.00, respectively. The winning province among the seven cities is Kütahya in Aegean Region. The provinces in the Aegean and Marmara Regions provide more optimum results for renewable energy installation than other regions. The results are closely related to the geographical features, wind speed, and solar radiation of the regions. In particular, the wind speed varies from 4.68 to 6.83 m/s in Aegean and Marmara Region, while it ranges from 2.56 to 4.24 m/s in Black Sea and Eastern Anatolia Region. The results also indicated the importance of wind speed and solar radiation in determining an economical system configuration.
- Considering the on-grid HRES, the lowest NPC were found in Çanakkale (Marmara), followed by İzmir (Aegean), Kırşehir (Central Anatolia), Gaziantep (South Eastern Anatolia), Erzurum (Eastern Anatolia), Adana (Mediterranean), and Çorum (Black Sea Region) at a NPC of $2,504.00, $3,303.00, $4,222.00, $4,763.00, $5,432.00, $5,472.00, and $7,172.00, respectively. It is clearly shown that the winning province is Çanakkale in Marmara Region for on-grid HRES. The highest NPC were $8,951.00, $8,473.00, $7,530.00, $7,323.00, $5,454.00, $4,805.00, $4,688.00 for Artvin (Black Sea), Ardahan (Eastern Anatolia), Çankırı(Central Anatolia),

Antalya (Mediterranean), Diyarbakır (South Eastern Anatolia), Edirne (Marmara) and Kütahya (Aegean), respectively. According to the results obtained from the simulation, the NPC values significantly increased in the provinces of Artvin and Ardahan, where WT installation could not be performed because of the low wind speed.

- From the investor's point of view, even though wind turbines are not installed in Artvin and Ardahan, installing a solar PV system allows the generation of renewable energy, thereby lowering both greenhouse-gas emissions and electricity bills.
- Depending on the increase in wind speed from east to west in Turkey, particularly in the Aegean and Marmara regions, in addition to the installation of solar panels, both electricity bills and greenhouse gas emissions can be reduced by installing wind turbines.
- CO_2 emissions lies between 182 kg/yr to 503 kg/yr for off-grid systems.
- From an environmental perspective, the lowest CO_2 emissions of stand-alone PV/WT/DG/BESS systems occurred in Yalova (Marmara), followed by Adana (Mediterranean), İzmir (Aegean), Çorum (Black Sea), Konya (Central Anatolia), Erzurum (Eastern Anatolia), and Diyarbakır (South Eastern Anatolia) at CO_2 levels of 182, 198, 201, 220, 224, 246, and 254 kg/yr, respectively. Considering the highest CO_2 emissions, HRES produced a total of 503, 341, 303, 272, 254, 244, and 228 kg/yr in Artvin (Black Sea), Elazığ (Eastern Anatolia), Adıyaman (South Eastern Anatolia), Antakya (Mediterranean), Çankırı(Central Anatolia), Kütahya (Aegean), and Çanakkale (Marmara), respectively.
- DG generates high energy to meet the load demand in Artvin, where the highest CO_2 emissions occur. Nonetheless, it should be noted that the pollutants released from DGs produce CO_2 emissions. Another factor affecting CO_2 emissions was the geographical features of the analyzed region. When the Marmara and Aegean regions are located in a mild climate zone, PV or WT can produce more energy, especially in the summer and autumn seasons, than the Black Sea region, where summers and winters are rainy.
- CO_2 emissions varies from 1,041 to 2,122 kg/yr for the grid-tied HRES.
- The lowest CO_2 emissions for each region were 1,041 kg/yr, 1,165 kg/yr, 1,258 kg/yr, 1,367 kg/yr, 1,411 kg/yr, 1,432 kg/yr, and 1,512 kg/year in Çanakkale (Marmara), İzmir (Aegean), Kırşehir (Central Anatolia), Adıyaman (South Eastern Anatolia), Adana (Mediterranean Coast), Erzurum (Eastern Anatolia), and Çorum (Black Sea), respectively, while the highest CO_2 emissions for each region occurred in Artvin (Black Sea), Ardahan (Eastern Anatolia), Antalya (Mediterranean Coast), Çankırı(Central Anatolia), Diyarbakır (South Eastern Anatolia), Yalova (Marmara), and Kütahya (Aegean) at a CO_2 level of 2,122 kg/yr, 2,104 kg/yr, 2,026 kg/yr, 1,518 kg/yr, 1,422 kg/yr, 1,300 kg/yr, and 1,268 kg/yr, respectively.
- It is clear that the pollutants from grid-connected HRES are higher than those from stand-alone HRES because electricity is drawn from the utility grid. Because wind turbines are not included in the HRES in the provinces of Artvin, Antalya, and Ardahan, more electricity was drawn from the utility grid to meet the energy demand.
- Although the installation of wind turbines in the mentioned 3 provinces is not recommended by the HOMER Software as the most optimal solution, the installation of WTs will increase the NPC value and decrease the amount of CO_2.
- The renewable fraction, such as CO_2 emissions, also depends on the location, geographical features, wind speed, solar radiation, and clearness index of the provinces analyzed. Because the utility grid is not available in stand-alone HRES, the renewable fraction to meet the demand is higher than that of grid-connected systems.
- Çanakkale in the Marmara Region has the lowest NPC among the 21 provinces for grid-tied and stand-alone systems. Stand-alone HRES in Çanakkale is optimally sized with a PV of 3.76 kW, a WT of 1.8 kW, a DG of 6.90 kW, a converter of 4 kW and 9 units of 22.6 kWh Li-ion battery. The grid-tied HRES in Çanakkale comprises a 5 kW PV, 1.8 kW WT, and a 3-kW converter.
- Artvin in the Black Sea Region has the highest NPC among the 21 provinces for on-grid and off-grid HRES. The stand-alone HRES in Artvin has a combination of 5.0 kW PV array, 3.60 kW WT, 6.90 kW DG, 4 kW converter, and 16 units of 40.2 kWh battery. The grid-connected HRES in Artvin contains a 5-kW PV array with a 3-kW converter.
- An "auto-size genset" was used for the stand-alone HRES design from the HOMER Pro Software, which automatically sizes itself to meet the load and match the load requirements. In the proposed system, the load demand is assumed to be the same for all provinces. Because there is no change in the load demand specific to provinces, the DG power shown in Table 8 is the same for all cases [30], [47], [97]. Since an "auto-size genset" is selected for DG in HOMER Software, it has a higher value than PV and WT.
- In the off-grid HRES, 98.2% of the energy was generated by the PV panels and wind turbines. A total of 1.82% of the energy was provided by the DG for the province of Çanakkale (Fig.18). Considering the grid-tied HRES, 88.1% of the energy produced was met by the PV panels and wind turbines. The remaining demand was satisfied by the utility grid (Fig.19).
- While 94.70% of the demand was satisfied by PV and WT in Artvin, 5.30% was supplied by DG for stand-alone HRES (Fig.20).

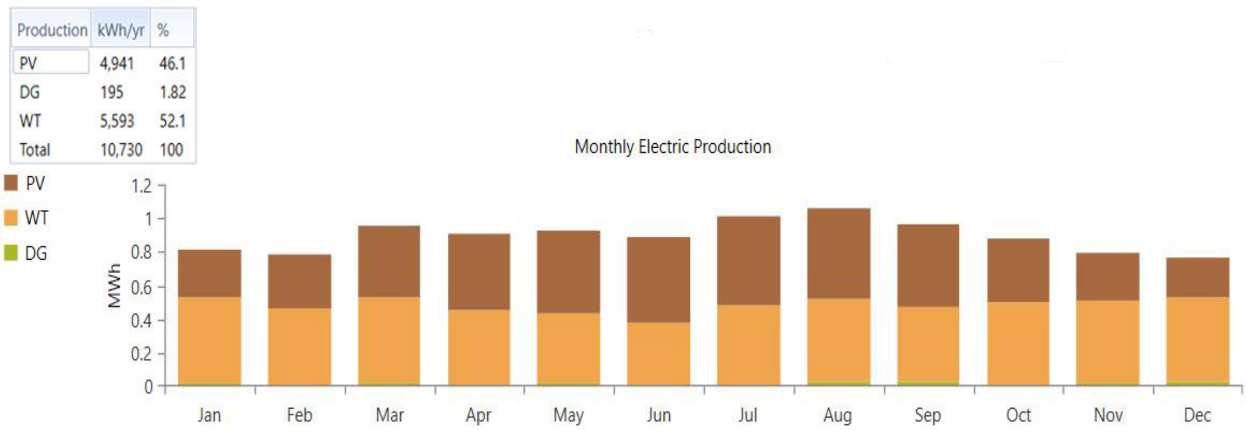


FIGURE 18. Monthly electricity production for stand-alone HRES in Çanakkale.

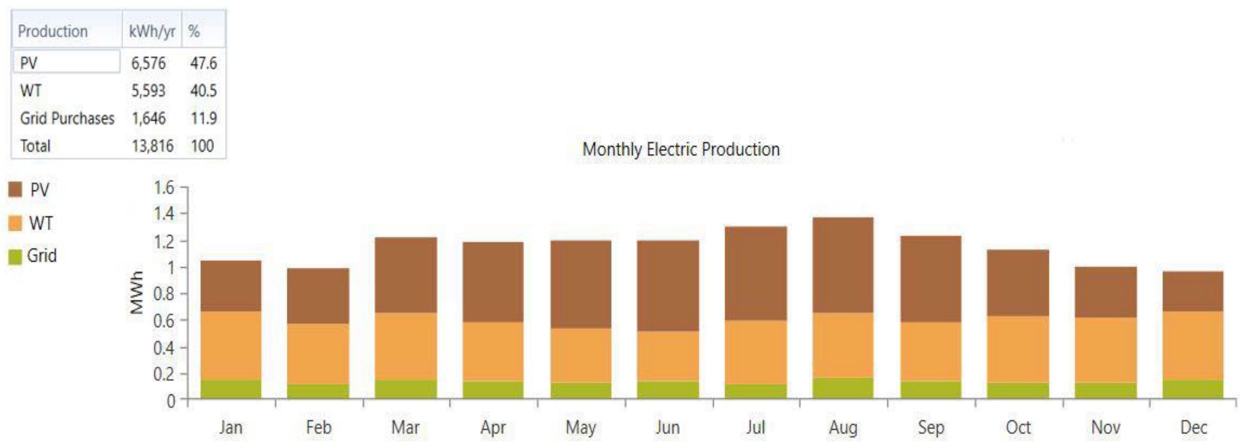


FIGURE 19. Monthly electricity production for grid-connected HRES in Çanakkale.

The electricity produced by the PV panels was 63.80% for on-grid HRES in Artvin. The remaining electrical energy produced by the grid was 36.2% (Fig.21).

- The renewable fraction ranges from 91.20% to 96.80% for off-grid HRES, whereas for grid-tied HRES, it ranges from 60.70% to 87.40%.

Table 9 shows a comparison of the grid-tied and stand-alone HRES presented in this study with some of the other studies considering the residential sector in the literature.

When Table 9 is examined, it can be observed that the results of the studies in the literature differ from each other and from the present HRES.

The fluctuations in NPC, COE, RF, and CO_2 were closely related to solar radiation, wind speed, load demand, and the location where the study was conducted. However, owing to Turkey's high solar radiation and wind speed, it generally has a lower NPC and COE, higher RF, and lower CO_2 emissions compared to the studies referenced in Table 9.

The comparative analysis using the solutions obtained indicates a reasonable trade-off with the studies in the literature and shows a clear comprehension of the feasibility of hybrid renewable energy systems in Turkey.

VII. SENSITIVITY ANALYSIS RESULTS

In the previous section, the optimized results for meeting the load demand for stand-alone and grid-connected HRES were presented. The optimized results contain variable parameters, such as the capital cost of the components and renewable energy sources. Therefore, it is aimed to eliminate the uncertainties according to the changing parameters by performing a sensitivity analysis. The 14 provinces that were subjected to the sensitivity analysis are listed in Table 8, with the lowest and highest NPC values for each region. Economic and technical sensitivity parameters were identified within the scope of the sensitivity analysis.

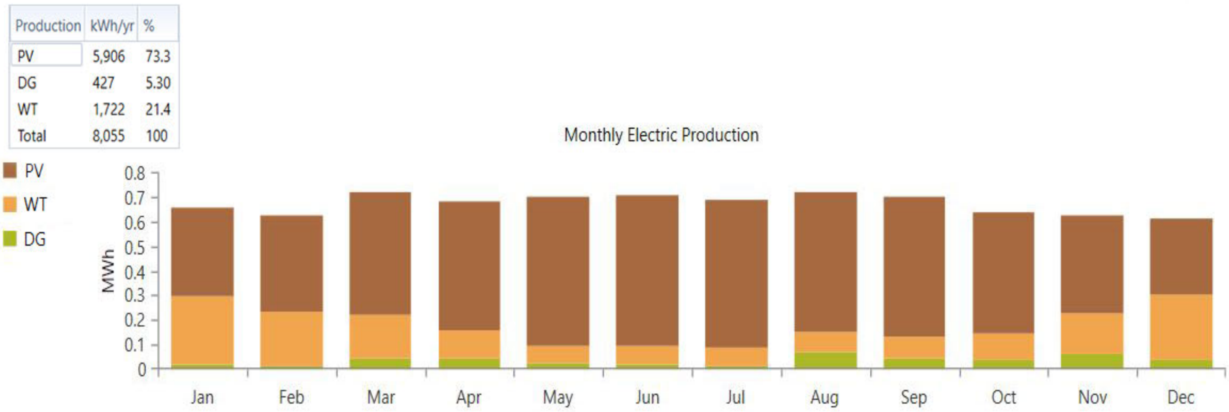


FIGURE 20. Monthly electricity production for stand-alone in Artvin.

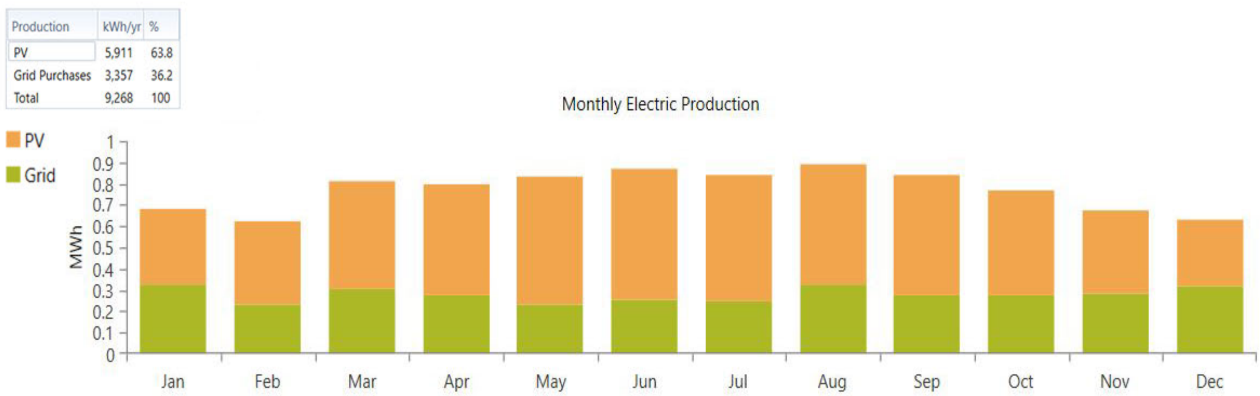


FIGURE 21. Monthly electricity production for grid-connected HRES in Artvin.

The variable parameters and scenarios for this research are given in Table 10. The optimization results for the sensitivity analysis are shown in Table 11.

A. ECONOMIC-RELATED SENSITIVITY ANALYSIS

The impacts of the capital cost of wind turbines and PV panels on stand-alone and grid-tied HRES are discussed in this section. According to Scenario titled A, as the capital cost multipliers of the PV and WT goes from 0.5 to 3 (except 1), the capital cost of the PV panels and wind turbines increases. There is no change in the capital cost of the PV panels and wind turbines if the capital cost multiplier equals 1.

Fig.22 presents the impact of the capital cost multiplier for stand-alone HRES in Artvin, which has the highest NPC values, whereas Fig.23 illustrates the impact of the capital cost multiplier for stand-alone HRES in Çanakkale, which has the lowest NPC values among the 14 provinces. The numerical values shown in the figures represent NPC values.

According to Fig.22 and Fig.23, a further decrease or increase in the capital cost multiplier does not change the system configuration for Artvin and Çanakkale. Moreover, a HRES with a combination of PV/WT/DG/BESS is the optimal solution for both provinces. NPC rose from \$37,518.110 to \$51,939.000 and from \$21,402.270 to \$29,978.890 for Artvin and Çanakkale, respectively, when the capital cost multiplier changed from 0.5 to 3. It was also observed that when the capital cost varies from 0.5 to 3, NPC and CO_2 emissions increased by 40.07% and 62.97%, respectively, and RF decreased by 2.07% for Çanakkale. Similarly, the NPC and CO_2 emissions increased by 38.44% and 53.57%, respectively, and RF decreased by 5.18% for Artvin. Compared to the province of Artvin, Çanakkale was more sensitive to parameter variations in NPC values. Fig.24 and Fig.25 depict the changes in the cost multiplier in the grid-connected HRES for Artvin and Çanakkale, respectively. Once the capital cost multiplier of the PV panels and WT varied from 0.5 to 3, it was seen that the system configuration changed in both provinces.

According to the results obtained from the sensitivity analyses, there were two different system configurations for

TABLE 9. Comparison of the results of present HRES with other research studies.

References	System Configuration	System Construction	NPC [$]	COE [$/kWh]	CO_2 [kg/yr]	RF [%]
[30]	Islanded	PV/WT/DG/BESS	643,674	0.198	26,455	64.5
[32]	Grid-tied	Grid/PV/WT/BESS	1,812	Unknown	1,804	Unknown
[36]	Grid-tied	Grid/PV	4,378	0.0382	Unknown	Unknown
[39]	Islanded	PV/WT/DG/BESS	722,356	0.137	84,007	64
[44]	Islanded	PV/DG/BESS	286,315	0.430	63,061	35
[50]	Islanded	WT/BESS	14,8486	0.309	0	100
[51]	Grid-tied	Grid/PV/BESS	Unknown	0.27-0.5217	Unknown	Unknown
[53]	Grid-tied	Grid/PV/BESS	6,682-8,819	0.071-0.092	52.7-1,730	54-61
[58]	Grid-tied	Grid/PV	1,366.9	Unknown	Unknown	Unknown
	Islanded	PV/DG/BESS	9,159.6	Unknown	44.5	Unknown
[59]	Grid-tied	Grid/WT/PV/BESS	1,627,833-3,589,056	0.037-0.219	40,959-614,386	53-96.8
	Islanded	WT/PV/BESS	4,060,031-8,925,135	0.288-0.695	0	100
[60]	Grid-tied	Grid/PV/BESS	5,974.12	0.562	3,009	30
[61]	Islanded	PV/DG/BESS	110,191	0.21	27,678	44.7
[62]	Islanded	PV/WT/DG/BESS	10,733-17,123	0.459-0.562	0-681	Unknown
[64]	Islanded	PV/DG/BESS	13,895	0.307	159	95.7
Present Study	Grid-tied	Grid/PVWT	2,540.00-8,951.00	0.01-0.051	1,041-2,122	60.70-87.40
	Islanded	PV/WT/DG/BESS	23,372-40,858	0.198-0.346	182-503	91.20-96.80

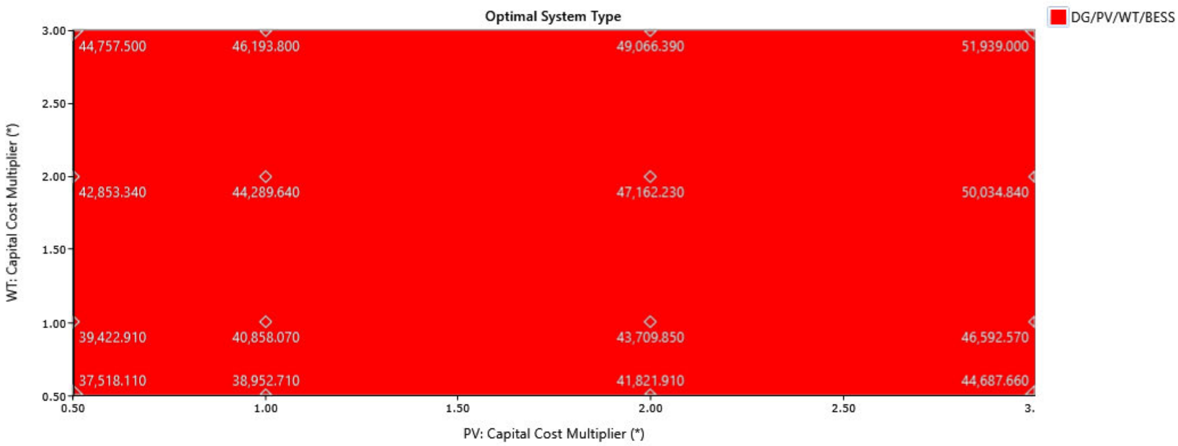


FIGURE 22. Change in NPC based on capital cost of PV and WT for stand-alone HRES in Artvin.

TABLE 10. The variable parameters and scenarios.

Variable Parameters	Units	Scenarios	Values
PV Capital Cost Multiplier	$	A	0.5, 1, 2, 3
WT Capital Cost Multiplier	$		0.5, 1, 2, 3
Solar Radiation	$kWh/m^2/day$	B	-10%, 0%, +10%, +20%
Wind Speed	m/s		-10%, 0%, +10%, +20%

Artvin and Çanakkale. Considering Fig.24, it is observed that the system configuration changed from Grid/PV to Grid-only when the capital cost multiplier of PV exceeded the threshold value of 1.5.

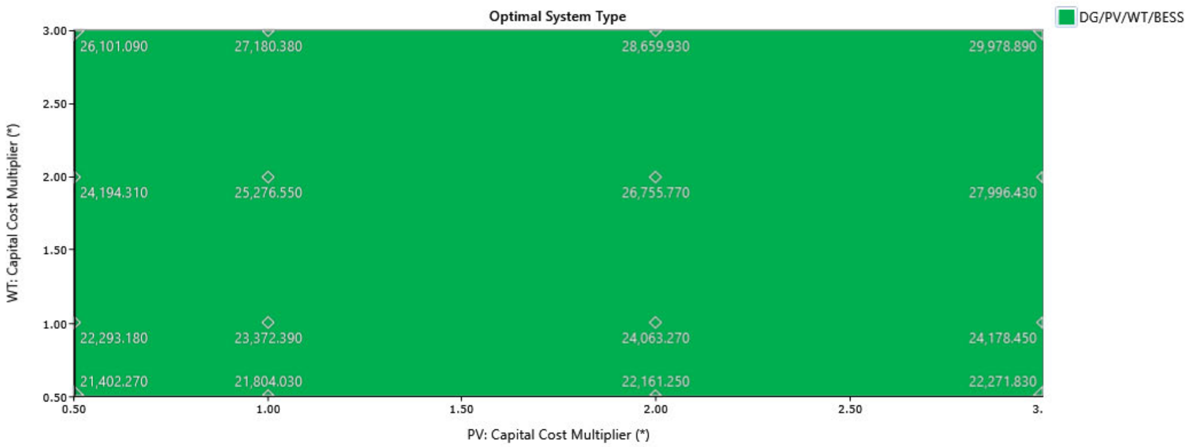


FIGURE 23. Change in NPC based on capital cost of PV and WT for stand-alone HRES in Çanakkale.

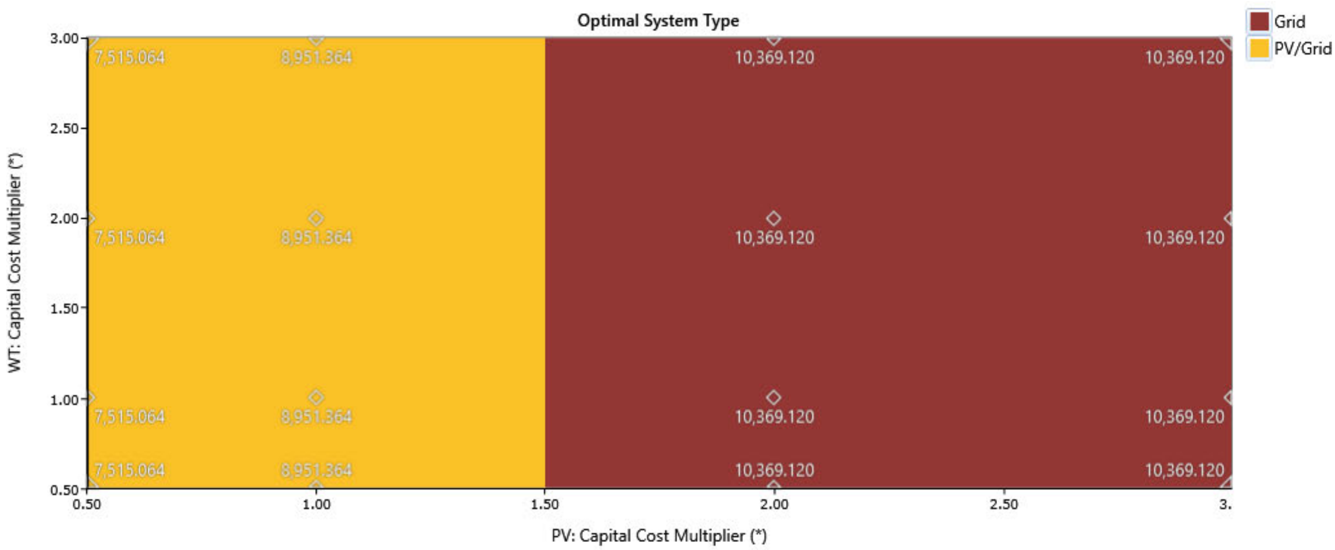


FIGURE 24. Change in NPC and optimum system configuration based on capital cost of PV and WT for grid-connected HRES in Artvin.

For the province of Çanakkale shown in Fig.25, with a cost multiplier greater than 1.64, the optimal configuration plan changed from Grid/PV/WT to Grid/WT.

It is clear that the parameter affecting the NPC values for both provinces is the capital cost multiplier of PV panels. When the analysis is performed with the same sensitivity parameters for Antalya, which is warmer than Çanakkale and does not receive as much precipitation as Artvin, it can be seen that 4 different system configurations: Grid-only, Grid/PV, Grid/WT, and Grid/PV/WT (Fig. 26). In addition to the cost multiplier of the WT and PV panels, the location of provinces affects the system configuration.

Increasing the capital cost multiplier for Artvin from 0.5 to 3 increased the NPC and CO_2 emission values by 37.97% and 44.18%, respectively, and decreased the RF from 60.72% to 0% in the grid-only system configuration considering Table 11.

Varying the capital cost multiplier from 0.5 to 3 raised CO_2 emissions by 42.52% and decreased RF by 19.61% for Çanakkale. It should be noted that Çanakkale is more affected by parameter changes considering the NPC value, whereas Artvin is more affected by CO_2 emissions and RF.

B. TECHNICAL-RELATED SENSITIVITY ANALYSIS

The solar radiation and wind speed parameters were varied in the technical-related sensitivity analysis to track their effects on the NPC, CO_2 emissions, and RF. The effects of solar radiation and wind speed on grid-tied and off-grid HRES were analyzed. In scenario titled B (Table 10), the percentages of solar radiation and wind speed ranged from 10% to 20% with an incremental increase of 10%. If the parameters were equal to 0%, no changes were observed in solar radiation and wind speed. Fig.27 and Fig.28 show the highest and lowest

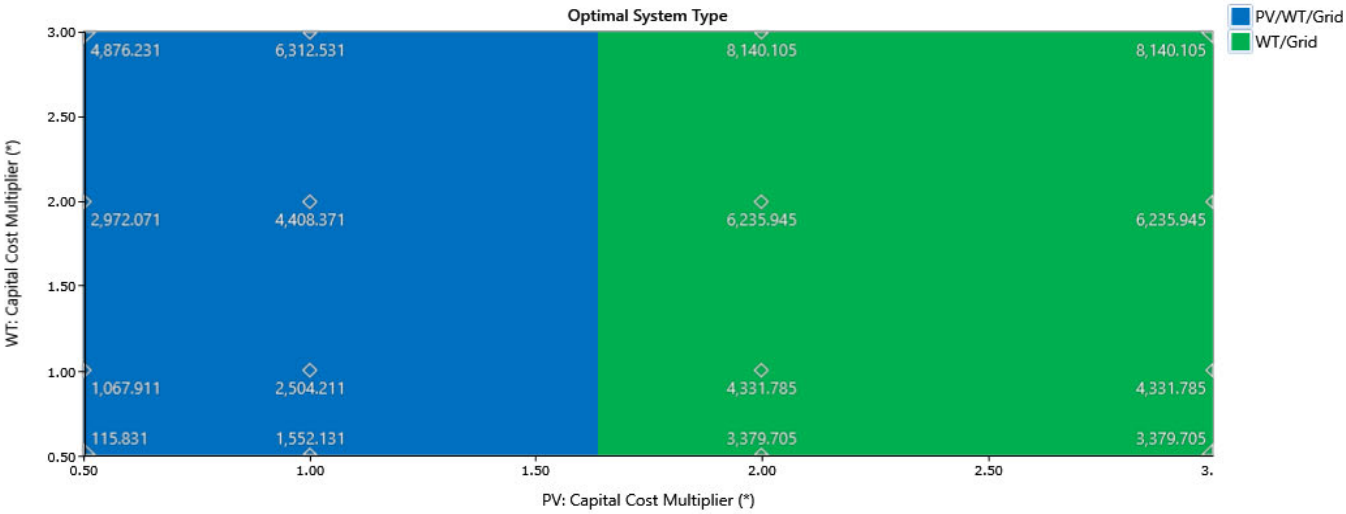


FIGURE 25. Change in NPC and optimum system configuration based on capital cost of PV and WT for grid-connected HRES in Çanakkale.

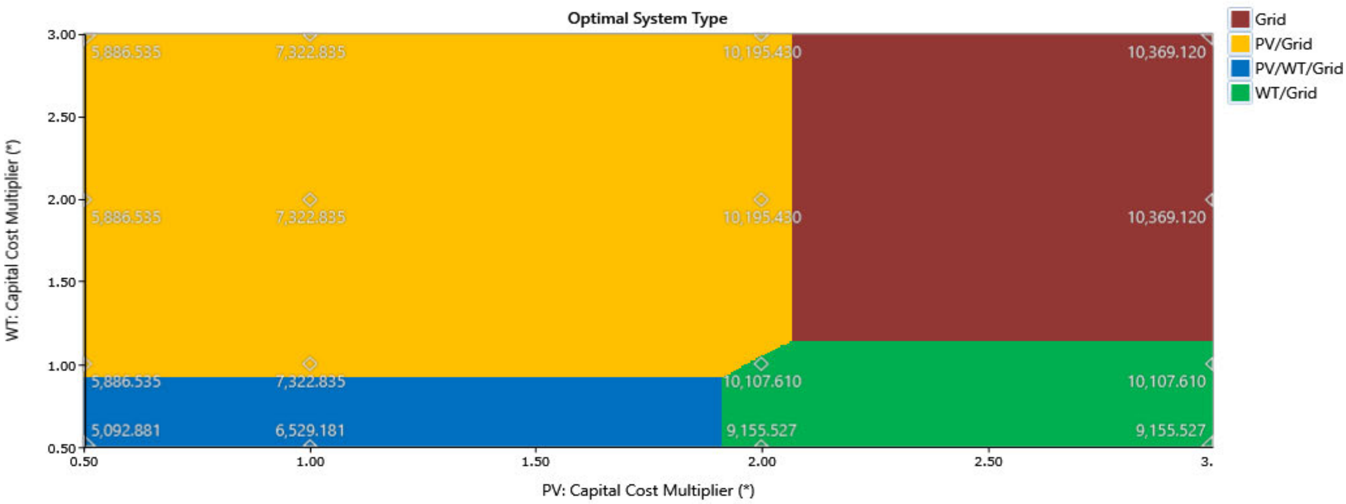


FIGURE 26. Change in NPC and optimum system configuration based on capital cost of PV and WT for grid-connected HRES in Antalya.

NPC values in the 14 provinces for stand-alone HRES in Artvin and Çanakkale, respectively.

NPC values are considered in all the figures presented in this section.

When parameters are changed, solar radiation values are within 3.24 – 4.32 kWh/m^2/day and 3.78 – 5.04 kWh/m^2/day ranges, respectively for Artvin and Çanakkale. Wind speed values vary from 2.304 to 3.072 m/s for Artvin, while the corresponding for Çanakkale are in the range of 6.14 and 8.19 m/s.

Fig.27 and Table 11 illustrate that an increase in solar radiation and wind speed values from −10% to +20% in Artvin led to a decrease in NPC by 25.58% and CO_2 emissions by 66.95%, and an increase in RF by 11.28%. Similarly, a 9.30% decrease in NPC, 9.23% decrease in CO_2 emissions, and 0.33% increase in RF were observed by varying the parameters of solar radiation and wind speed at the same rate in Çanakkale. It is clearly seen that since Çanakkale has a higher wind and solar energy potential than Artvin, it is less affected by the changes in parameters. Fig.29 and Fig.30 show the impacts of varying solar radiation and wind speed on the NPC value for grid-connected HRES in Artvin and Çanakkale, respectively.

Considering Fig.29, when the solar radiation and wind speed values fluctuate from 3.24 to 4.32 kWh/m^2/day and from 2.30 to 3.072 m/s, respectively, it is obvious that the NPC decreases from \$9,773.972 to \$7,361.022. Similarly, according to the Fig.30, it is clearly seen that there is a significant decrease in NPC value in Çanakkale when the solar radiation and wind speed increase by up to 3.78 kWh/m^2/day and 6.147 m/s from 8.196 kWh/m^2/day and 2.30 m/s, respectively. When there was an increase in solar radiation and

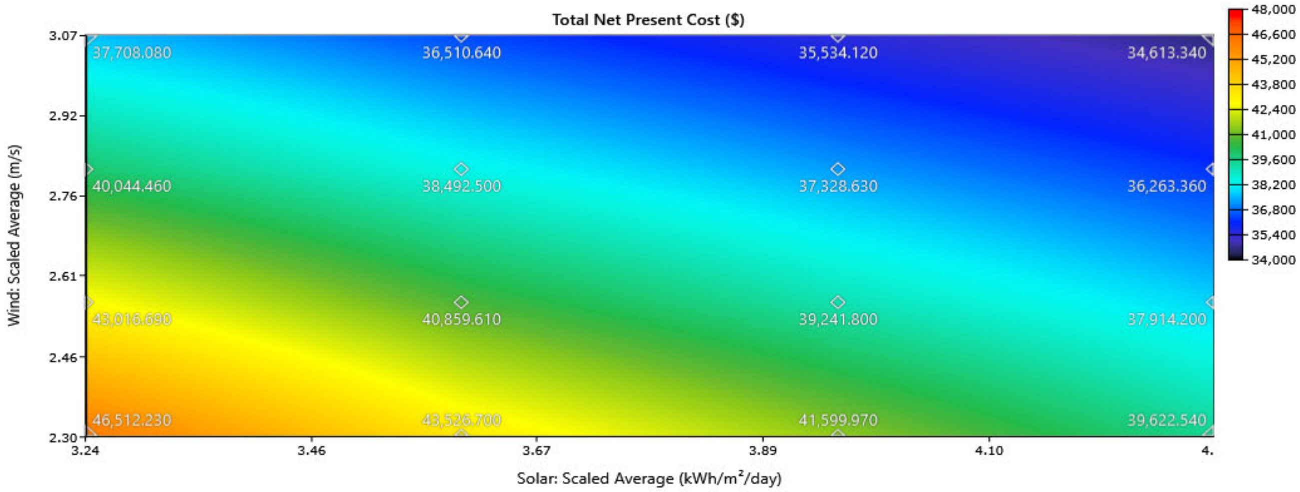


FIGURE 27. Change in NPC based on solar radiation and wind speed for stand-alone HRES in Artvin.

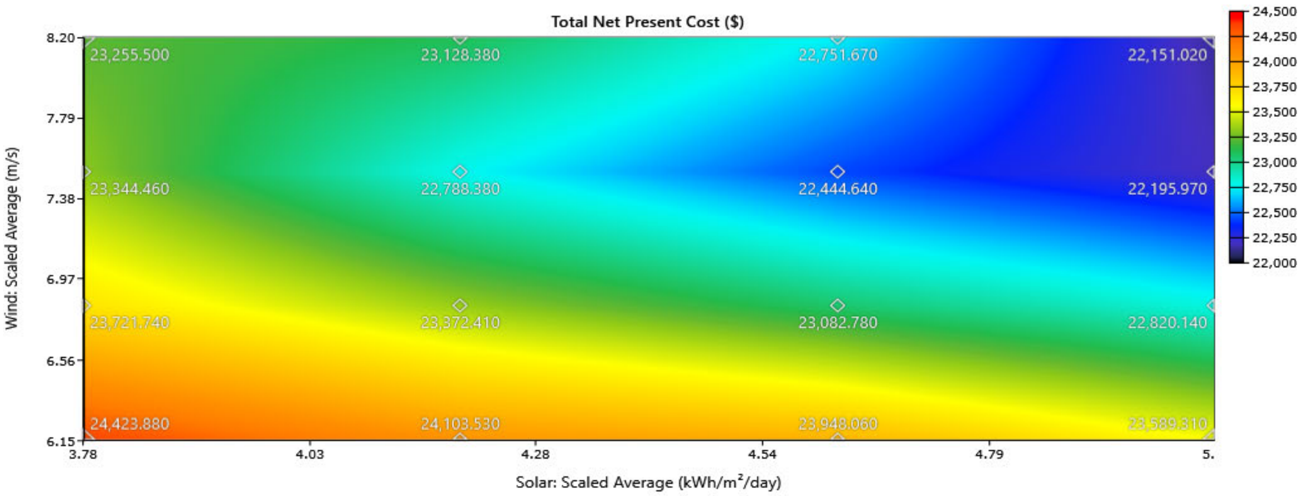


FIGURE 28. Change in NPC based on solar radiation and wind speed for stand-alone HRES in Çanakkale.

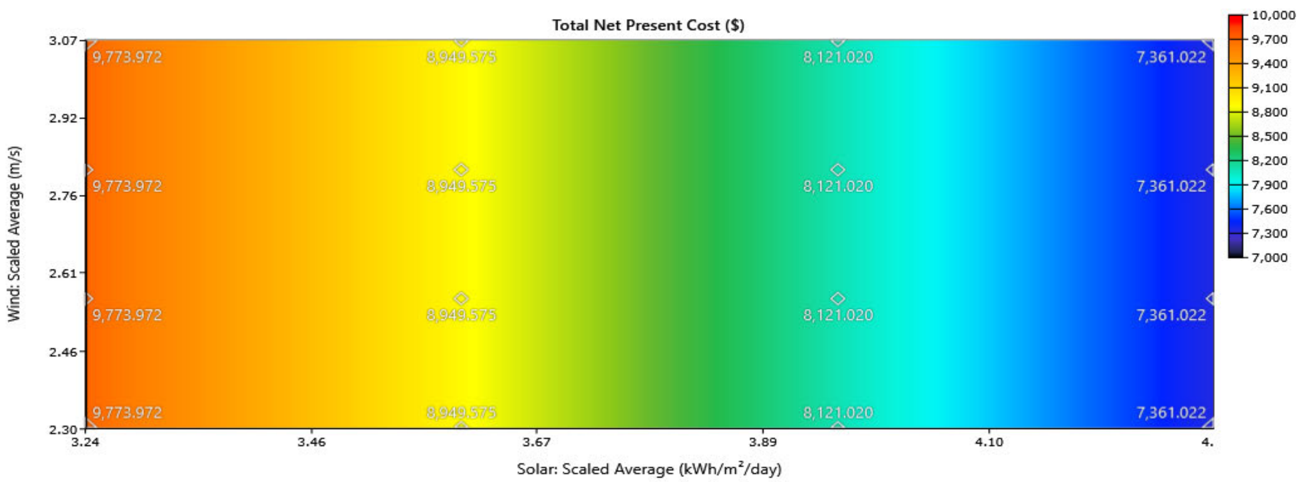


FIGURE 29. Change in NPC based on solar radiation and wind speed for grid-connected HRES in Artvin.

wind speed from −10% to +20%, it was observed that the decrease rate of NPC value was higher in Çanakkale, and it decreased approximately 3.59 times more than that of Artvin. In addition to the sensitivity analyses carried out thus far, the effects of the change in battery costs on NPC were investigated in this study. In one study, it was estimated that

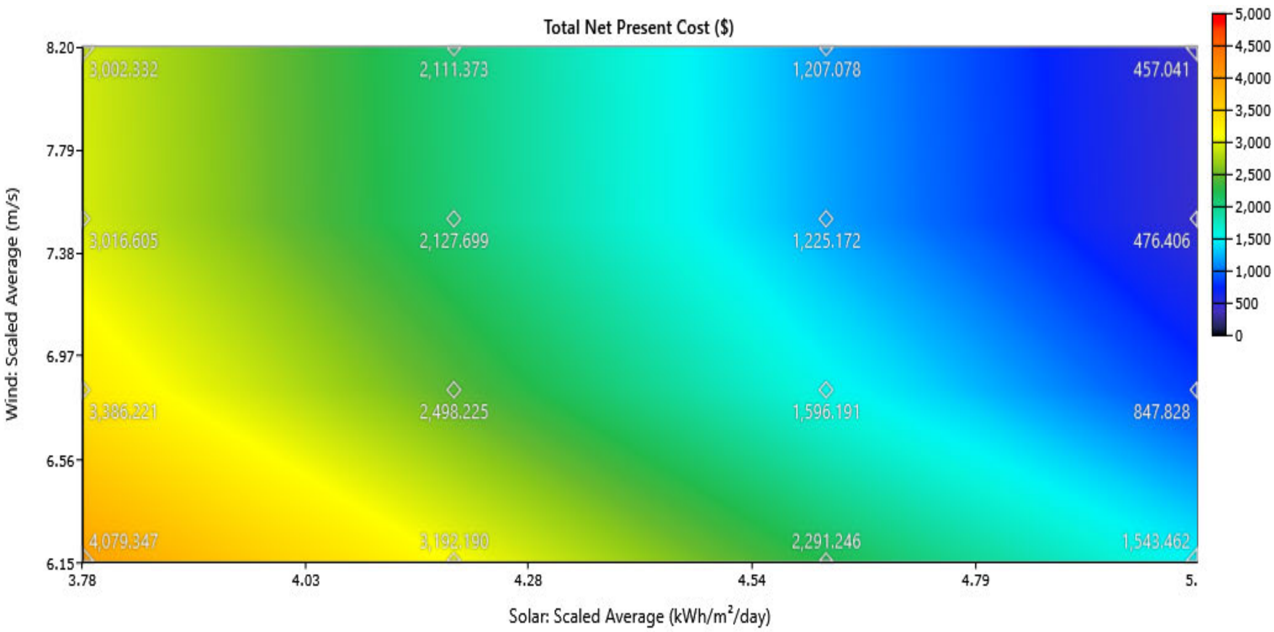


FIGURE 30. Change in NPC based on solar radiation and wind speed for grid-connected HRES in Çanakkale.

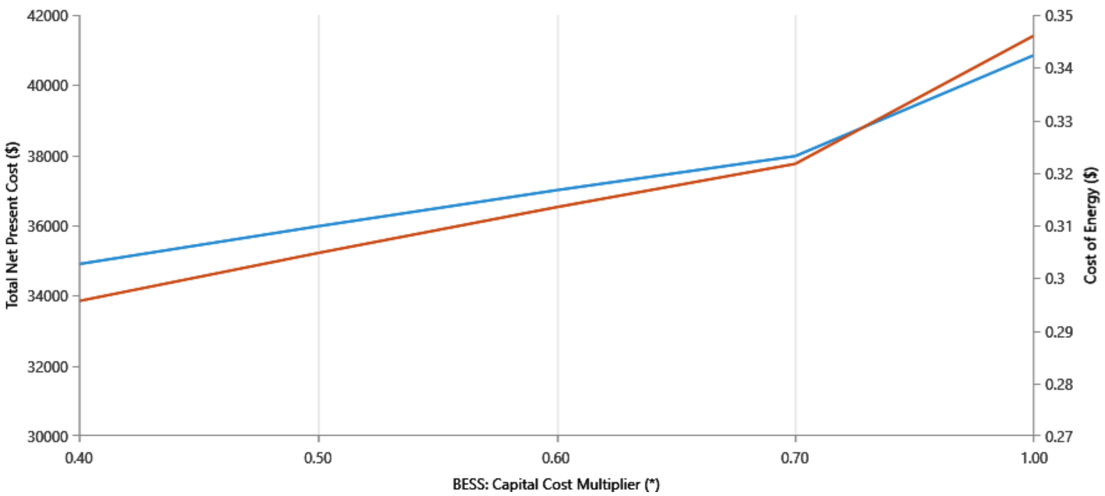


FIGURE 31. The effect of change of battery capital cost multiplier on NPC and COE in Artvin.

battery costs will be between 70 kWh/$ and 90 kWh/$ by 2050 [98]. Moreover, it is predicted that the impact of developing technologies and developments in battery management systems will have significant effects on the battery market and future battery cost reductions [98], [99]. In this context, the battery capital cost multipliers used in HRES systems in the provinces of Artvin, Antalya, and Çanakkale were selected as 0.4, 0.5, 0.6, 0.7, and 1, respectively, and their effects were evaluated within the scope of sensitivity analysis. The selected coefficients were entered into HOMER Pro based on the kWh/$ value according to [98]. The sensitivity analysis results of the stand-alone HRES of the selected provinces are shown in Fig. 31, Fig. 32, and Fig. 33 for Artvin, Antalya, and Çanakkale, respectively.

In the figures, the blue line shows the NPC, whereas the red line indicates the COE. According to Figures 31-33, when the battery capital cost multiplier was reduced from 1 to 0.4, Çanakkale had the lowest NPC and COE values, whereas Artvin had the highest NPC and COE values. It was observed that the decrease in battery cost for Çanakkale reduced the NPC and COE by 15.09% and 15.15%, respectively, while it was found that the NPC and COE values decreased by 14.58% and 14.45% for the province of Artvin, respectively. On the other hand, Antalya, which provides 15.97% and 16.13%

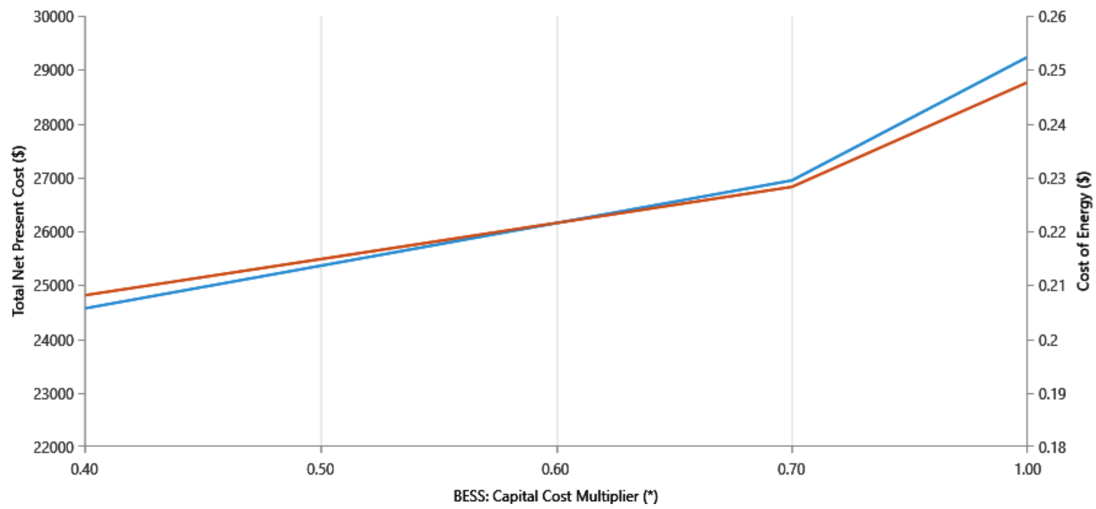


FIGURE 32. The effect of change of battery capital cost multiplier on NPC and COE in Antalya.

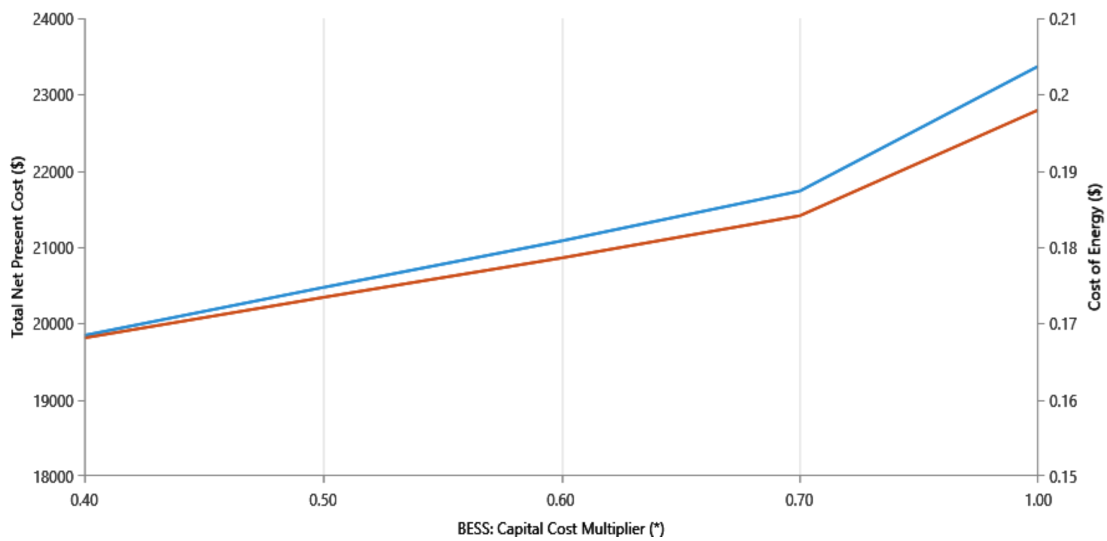


FIGURE 33. The effect of change of battery capital cost multiplier on NPC and COE in Çanakkale.

reductions in NPC and COE, respectively, is the province with the highest cost reduction compared to Artvin and Çanakkale.

VIII. CONCLUSION

Although Turkey has high solar radiation and relative wind speed, rooftop photovoltaic systems and wind turbines have not become widespread in Turkey; therefore, renewable energy opportunities are not sufficiently utilized in Turkey. In addition, the techno-economic and environmental effects of grid-connected and stand-alone HRES were investigated using the HOMER Pro software in this study owing to the lack of studies on renewable energy using solar and wind energy in Turkey. Because of Turkey's regional solar radiation and wind speed diversity, analyses were carried out on provinces in different regions of Turkey. Because the solar energy potential in Turkey is higher than the wind energy potential, considering the highest, median, and lowest solar radiation in seven regions of Turkey, a total of 21 provinces were selected and analyzed. The electricity consumption of a family of four was measured using smart plugs to create a realistic and accurate residential load profile in the techno-economic and environmental analyses carried out on a total of 21 provinces in seven regions of Turkey due to climate diversity. In this context, the daily consumption of a four-person Turkish household as a residential load is determined as 13.26 kWh on average. The main conclusions of the analyses are as follows:

- Considering the grid-connected HRES, the optimum solution is provided by the Grid/PV/WT for many provinces. In addition, it is also seen that the most optimum solution is Grid/PV in some provinces where the wind speed is low or insufficient from a technical perspective.

TABLE 11. Optimization results for sensitivity analysis.

Provinces	Scenario A	Off-grid			On-grid			Scenario B	Off-grid			On-grid		
		NPC ($)	CO_2 (kg/yr)	RF (%)	NPC ($)	CO_2 (kg/yr)	RF (%)		NPC ($)	CO_2 (kg/yr)	RF (%)	NPC ($)	CO_2 (kg/yr)	RF (%)
Yalova	0.5	24,392.64	156	97.21	3,010.30	1,258	82.82	-10%	29,036.99	249	95.55	7,328.21	1,359	79.57
	1	27,233.88	182	96.75	5,398.68	1,258	82.82	0%	27,233.94	182	96.75	5,393.59	1,258	82.83
	2	31,828.52	323	94.26	8,866.60	1,754	59.09	+10%	25,524.96	228	95.94	3,577.53	1,173	85.48
	3	35,972.32	326	94.24	10,369.12	3,059	0.00	+20%	24,122.48	164	97.09	2,142.75	1,115	87.04
Çanakkale	0.5	21,402.27	177	96.92	115.83	1,041	87.37	-10%	24,423.88	195	96.57	4,079.35	1,095	85.68
	1	23,372.39	228	95.97	2,504.21	1,041	87.37	0%	23,372.41	228	95.97	2,498.23	1,041	87.37
	2	26,755.77	249	95.64	6,235.95	1,498	70.23	+10%	22,444.64	200	96.49	1,225.17	1,013	85.55
	3	29,978.89	288	94.91	8,140.11	1,498	70.23	+20%	22,151.02	177	96.89	457.04	1,023	88.86
Kütahya	0.5	24,121.52	151	97.31	2,300.00	1,252	83.79	-10%	28,835.28	174	96.92	6,686.47	1,358	80.39
	1	26,534.86	244	95.67	4,688.39	1,252	83.79	0%	26,525.78	245	95.67	4,686.18	1,251	83.80
	2	30,947.73	260	95.40	8,978.16	1,762	58.56	+10%	25,075.43	209	96.30	2,746.61	1,166	86.16
	3	34,847.96	279	95.04	10,369.12	3,059	0.00	+20%	23,819.36	193	96.59	1,208.95	1,113	87.63
İzmir	0.5	22,909.51	174	96.93	915.01	1,165	85.57	-10%	27,097.56	262	95.39	5,318.78	1,265	82.83
	1	25,135.08	201	96.46	3,303.39	1,165	85.57	0%	25,133.19	200	96.46	3,299.79	1,165	85.58
	2	29,197.80	241	95.74	8,038.35	1,674	62.99	+10%	23,703.61	191	96.62	1,453.84	1,088	87.71
	3	33,008.29	271	95.19	9,942.51	1,674	62.99	+20%	22,615.79	179	96.83	99.96	1,034	88.94
Antalya	0.5	26,849.78	267	95.31	5,092.88	1,501	77.90	-10%	32,045.63	312	94.51	8,269.73	2,008	63.67
	1	29,237.09	267	95.31	7,322.84	1,976	66.39	0%	29,241.09	267	95.31	7,330.75	1,977	66.37
	2	34,012.73	267	95.32	10,195.43	1,976	66.39	+10%	27,531.20	229	95.97	5,719.63	1,402	81.31
	3	38,559.23	251	95.59	10,369.12	3,059	0.00	+20%	26,357.15	226	96.03	4,121.61	1,312	83.69
Adana	0.5	25,136.13	189	96.69	3,083.27	1,422	81.38	-10%	29,146.74	260	95.44	7,300.67	2,006	66.19
	1	27,348.24	198	96.52	5,471.65	1,422	81.38	0%	27,358.13	198	96.53	5,477.80	1,423	81.37
	2	31,523.67	219	96.15	9,179.17	1,985	69.13	+10%	25,875.31	213	96.26	3,471.06	1,324	84.13
	3	35,545.66	256	95.48	10,369.12	3,059	0.00	+20%	24,613.18	209	96.36	1,795.28	1,243	86.09
Çankırı	0.5	27,995.28	254	95.50	5,141.14	1,518	78.00	-10%	34,115.74	305	94.61	8,582.50	2,050	62.42
	1	31,287.37	254	95.50	7,529.52	1,518	78.00	0%	31,283.34	273	95.16	7,543.91	1,519	77.98
	2	36,059.72	407	92.81	10,369.12	3,059	0.00	+10%	28,908.98	311	94.51	5,656.82	1,424	81.17
	3	40,662.67	413	92.72	10,369.12	3,059	0.00	+20%	27,227.09	240	95.76	3,997.90	1,335	83.59
Kırşehir	0.5	24,142.45	209	96.29	1,834.01	1,268	84.03	-10%	28,614.79	291	94.86	6,230.71	1,365	80.85
	1	26,521.21	241	95.74	4,222.39	1,268	84.03	0%	26,505.11	241	95.74	4,206.39	1,267	84.06
	2	30,794.48	283	94.99	8,764.82	1,739	59.65	+10%	24,830.58	204	96.36	2,231.81	1,188	86.30
	3	34,579.73	288	94.90	10,369.12	3,059	0.00	+20%	23,656.58	218	96.13	723.02	1,127	87.77
Artvin	0.5	37,518.11	503	91.18	7,515.06	2,122	60.72	-10%	46,512.24	817	85.61	9,773.97	2,146	57.82
	1	40,858.07	503	91.18	8,951.36	2,122	60.72	0%	40,859.61	503	91.18	8,949.58	2,121	60.73
	2	47,162.23	772	86.46	10,369.12	3,059	0.00	+10%	37,328.63	422	92.60	8,121.02	2,101	63.96
	3	51,939.00	772	86.46	10,369.12	3,059	0.00	+20%	34,613.34	270	95.27	7,361.02	2,083	65.99
Çorum	0.5	27,333.03	220	96.10	4,783.92	1,512	78.55	-10%	33,069.20	297	94.72	8,362.85	2,050	63.05
	1	30,658.89	220	96.10	7,172.31	1,512	78.55	0%	30,639.47	220	96.10	7,164.19	1,511	78.56
	2	35,331.39	349	93.82	10,288.48	2,026	66.35	+10%	28,204.71	278	95.08	5,262.05	1,415	81.66
	3	39,868.86	417	92.63	10,369.12	3,059	0.00	+20%	26,661.96	234	95.86	3,622.60	1,330	83.95
Ardahan	0.5	29,808.46	304	94.61	6,393.57	1,626	74.68	-10%	35,623.62	326	94.24	9,313.16	2,128	59.52
	1	33,098.48	304	94.61	8,473.15	2,104	62.28	0%	32,511.54	265	95.29	8,462.59	2,104	62.31
	2	38,947.90	433	92.33	10,369.12	3,059	0.00	+10%	30,512.11	241	95.71	6,763.08	1,505	79.12
	3	43,717.40	433	92.33	10,369.12	3,059	0.00	+20%	28,550.06	288	94.89	5,146.07	1,413	81.79
Erzurum	0.5	26,365.67	237	95.80	3,043.70	1,452	81.14	-10%	30,715.54	295	94.78	7,336.77	1,556	77.55
	1	28,650.94	246	95.66	5,432.08	1,452	81.14	0%	28,503.74	239	95.77	5,218.84	1,451	81.36
	2	33,164.87	247	95.29	9,336.16	2,033	68.40	+10%	26,940.48	267	95.28	3,233.16	1,358	84.01
	3	37,299.99	314	94.45	10,369.12	3,059	0.00	+20%	25,434.00	183	96.73	1,624.96	1,276	85.90
Diyarbakır	0.5	35,044.97	446	92.10	3,065.94	1,432	81.30	-10%	31,510.39	278	95.10	7,408.49	1,534	77.67
	1	38,632.81	563	90.08	5,454.32	1,432	81.30	0%	28,793.74	254	95.52	5,440.62	1,431	81.32
	2	44,179.57	607	89.22	9,625.15	2,030	67.81	+10%	26,879.37	222	96.06	3,416.62	1,338	84.04
	3	45,979.93	435	92.29	10,369.12	3,059	0.00	+20%	25,563.30	233	95.88	1,769.80	1,264	85.91
Gaziantep	0.5	25,838.48	190	96.63	2,374.53	1,367	82.60	-10%	30,814.05	417	92.65	6,764.52	1,465	79.20
	1	28,365.77	281	95.05	4,762.91	1,367	82.60	0%	28,366.84	281	95.05	4,764.25	1,367	82.60
	2	32,934.82	297	94.75	9,539.67	1,367	82.60	+10%	26,567.66	257	95.47	2,779.40	1,285	85.02
	3	36,979.43	419	92.61	10,369.12	3,059	0.00	+20%	25,148.47	199	96.50	1,188.17	1,209	86.77

- Unlike grid-connected HRES, a stand-alone HRES with a combination of PV/WT/DG/BESS is an optimum solution and is technically feasible for all provinces.
- The NPC value of the grid-connected HRES lies between \$2,504.00 to \$8,951.00. The Grid/PV/WT hybrid system has a lower NPC value than the Grid/PV hybrid system.
- The NPC value is economically quite high in a stand-alone HRES compared to a grid-connected HRES. The value of NPC varies from \$23,372.00 to \$40,858.00, depending on the changes in the wind speed and solar radiation of the geographical locations of the provinces for off-grid HRES.
- Stand-alone HRES for Çanakkale in Marmara region, which has the lowest NPC value, consists of a 3.76 kW PV array, a 6.90 kW DG, a 1.80 kW WT, and 22.6 kWh batteries, while stand-alone HRES for Artvin in Black Sea Coast Region, which has the highest NPC value, contains a 5 kW PV array, two WT units of 1.80 kW each, a 6.90 kW DG, and 40.2 kWh batteries.
- Similarly, the grid-tied HRES for Çanakkale is optimally sized with a 5 kW PV array, a 1.80-kW WT, and a 3-kW converter. On the other hand, the stand-alone HRES for Artvin only consists of a 5-kW PV array and a 3-kW converter.
- PV/WT/DG/BESS systems are technically feasible in both Çanakkale and Artvin for off-grid HRES. In addition, Grid/PV/WT and Grid/PV are technically feasible in Çanakkale and Artvin, respectively, for an on-grid HRES.
- When the grid-tied HRES are examined from an environmental point of view, it is found that the hybrid use of grid-integrated PVs and WT is a more environmentally friendly system than using grid-integrated PVs. Moreover, it can be said that grid-tied HRES produces a higher amount of CO_2 than stand-alone HRES.
- Considering the stand-alone HRES, it was observed that provinces in the Marmara and Aegean regions had lower CO_2 emissions than those in the Black Sea Coast, Eastern Anatolia, and South Eastern Anatolia regions.
- CO_2 emissions lie between 1,041 and 2,122 kg/yr for grid-tied HRES, whereas they range from 182 to 503 kg/yr for stand-alone HRES.

The findings related to the sensitivity analysis performed for grid-tied and stand-alone HRES are presented as follows:

- The increase or decrease in the capital cost of the PV and WT does not change the system configuration for a stand-alone HRES. The PV/WT/DG/BESS systems are technically feasible solutions for all provinces. In contrast, it can be seen clearly that the system configuration changes depending on the change in the capital costs of the PV and WT for the grid-tied HRES.
- A variation in the capital cost of PV and WT from 0.5 to 3 resulted in an increase in NPC and CO_2 emissions for all provinces, considering the grid-connected and stand-alone HRES. Specifically, for Çanakkale, there was a 40.07% increase in NPC and a 62.97% increase in CO_2 emissions, whereas for Artvin, the increase was 38.44% and 53.57% for NPC and CO_2 emissions, respectively, for stand-alone HRES.
- The increase in the capital cost multiplier from 0.5 to 3 in Artvin led to a rise of 44.18% in CO_2 emissions. However, for Çanakkale, varying the capital cost multiplier in the same range resulted in a 42.52% increase in CO_2 emissions for grid-tied HRES.
- It was found that the amount of CO_2 generally decreases as the solar radiation and wind speed increase for grid-connected and stand-alone HRES, considering the selected provinces.
- The findings indicate that in Çanakkale, there was a 9.30% reduction in NPC and a 9.23% reduction in CO_2 emissions when solar radiation and wind speed increased. In Artvin, however, the reduction was more significant, with NPC decreasing by 25.58% and CO_2 emissions decreasing by 66.95% for stand-alone HRES. Considering the grid-tied HRES, a higher decrease rate in the NPC value was observed in Çanakkale, and this reduction was approximately 3.59 times more than that observed in Artvin.
- Based on the sensitivity analysis of the simulation results, it was found that the provinces with higher wind speed and solar energy potential were less affected by the parameter changes.
- It was found that the NPC and COE values decreased when the capital cost of BESS decreased for stand-alone HRES. Because battery costs are predicted to decrease in the near future, the investment costs of battery-based renewable energy systems are expected to decrease.

This study, in which simulation analyses were carried out, first draws the attention of customers living in both urban and rural areas in developing countries, and then policymakers, investors, and stakeholders. The findings can help policymakers and stakeholders make effective policy decisions and can lead to much greater growth in renewable energy.

In future work, in addition to PV and WT, other renewable energy sources, such as biomass and geothermal energy, will also be included in the analyses to examine the optimal design of the HRES. Furthermore, a comparative analysis of grid-tied and stand-alone HRES will be performed to more precisely size the system components, such as diesel generators and PV panels according to the changing residential load profiles. The impact of residential load change, PV panel efficiency variation, and ambient temperature variability on the NPC will be investigated in the sensitivity analysis. Finally, alternative software, such as RETScreen, PVSyst, and SAM, may be utilized to evaluate the feasibility and performance of renewable energy projects and optimize system design instead of HOMER Pro Software. Especially with the use of PVSyst software, the area where PV panels will be installed can be determined, and thus, the sizing of them can be more accurately performed.

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