TECHNICAL AND ECONOMIC EVALUATION OF A STANDALONE AND GRID CONNECTED HYBRID RENEWABLE ENERGY SYSTEM: CASE STUDY AT ESKIŞEHIR TECHNICAL UNIVERSITY

Master's Thesis

Hussein Kerow Adan

Eskişehir 2020

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Department of Advanced Technologies

Energy Resources and Management Program

Supervisor: Assoc. Prof. Dr. Ümmühan BAŞARAN FİLİK

Eskişehir

Anadolu University

Institute of Graduate Programs

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ABSTRACT

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As a result of increase in energy demand and population, renewable energy is being utilized around the world especially hybrid renewable system because it utilizes the strength of one energy sources to balance the weakness of the other making the system reliable, less costly and polluting, but the hybrid system should be optimally sized to make it economically attractive. Therefore, the objective of the thesis is to determine the technical and economic evaluation as well as environmental impact of a standalone and grid interactive hybrid renewable energy system to supply electricity to an Electrical and Electronics Engineering Department in Eskişehir Technical University.

Hybrid optimization model for multiple energy resources (HOMER) pro software was preferred to achieve the optimal configuration of the standalone and grid interactive hybrid system. Then, the two system is compared to see the most economical one according to the net present cost (NPC) and cost of energy (COE). The results revealed that the most optimal configuration of the two system is PV/grid hybrid system with 198 kW solar panel and the grid. it has NPC of $1.68M and COE of 0.176 $/kWh but not environmentally friendly when compared to the standalone hybrid system because of low renewable fraction.

In this thesis, problems related to reliability, cost and environmental concerns of traditional energy sources are solved by using hybrid renewable energy system. The outputs of the thesis can assist stakeholders and policy makers in the growth of a standalone and grid interactive hybrid renewable system.

Keywords: Technical and economic evaluation, Hybrid optimization model for multiple energy resources (HOMER), Net present cost (NPC), Cost of energy (COE), Standalone and grid interactive hybrid system, Sensitivity analysis.

ÖZET

ŞEBEKEYE BAĞIMSIZ VE BAĞIMLI HIBRID YENILENEBILIR ENERJI SISTEMI TEKNIK VE EKONOMIK DEĞERLENDIRILMESI: ESKIŞEHIR TEKNİK ÜNİVERSİTESİNDE VAKA ÇALIŞMASI

HUSSEIN KEROW ADAN

İleri Teknolojiler Anabilim Dalı

Enerji Kaynakları ve Yönetimi Bilim Dalı

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Danışman: Doç. Dr. Ümmühan BAŞARAN FİLİK

Yüksek enerji talebi, nüfus artışı ve fosil yakıtların tükenmesinin bir sonucu olarak, sistemi güvenilir, uygun maliyetli ve çevre dostu hale getiren çeşitli enerji kaynaklarını birleştirdiği için özellikle hibrit sistem olmak üzere dünya çapında yenilenebilir enerji kullanılmaktadır, ancak hibrit sistem ekonomik olarak çekici hale getirmek, optimum boyutta olmalıdır. Bu nedenle tezin amacı, Eskişehir Teknik Üniversitesi Elektrik-Elektronik Mühendisliği Bölümü'ne elektrik sağlamak için bağımsız ve bir şebeke üzerinde hibrit enerji sisteminin teknik, ekonomik ve çevresel etki değerlendirmesini belirlemektir.

Bağımsız ve şebeke hibrit sisteminin optimum yapılandırmasını sağlamak için çoklu enerji kaynakları (HOMER) pro yazılımı için hibrit optimizasyon modeli kullanıldı. Daha sonra, iki sistem, mevcut net maliyet (NPC) ve enerji maliyetine (COE) göre en ekonomik olanı görmek için karşılaştırılmıştır. Sonuçlar göre, iki sistemin en uygun konfigürasyonunun 198 kW güneş paneli ve şebeke yapısından oluşan hibrit sistemi olduğu ortaya koyulmuştur. 1,68 milyon dolarlık NPC ve 0.176 $ / kWh COE'ye sahiptir, ancak düşük yenilenebilir fraksiyon nedeniyle bağımsız hibrit sistemle karşılaştırıldığında çevre dostu olmadığı söylenebilir.

Bu tezde, hibrit yenilenebilir enerji sistemi kullanılarak, geleneksel enerji kaynaklarının güvenilirlik, maliyet ve çevresel kaygıları ile ilgili sorunlar çözülmeye çalışılmıştır. Tezin çıktıları, paydaşlara ve politika yapıcılara bağımsız ve şebeke etkileşimli hibrit yenilenebilir sistemin büyümesinde yardımcı olabilecektir. Bağımsız ve şebeke etkileşimli hibrit sistemin simülasyonunu gerçekleştirerek, müşterilerin ister ekonomik ister çevresel endişeleri olsun, ilgilerine bağlı olarak seçim yapmalarını sağlayacaktır.

Anahtar Sözcükler: Teknik ve ekonomik değerlendirme, Çoklu enerji kaynakları için hibrit Optimizasyon Modeli (HOMER), Net bugünkü maliyet (NPC), Enerji maliyeti (COE), Şebekeye bağımsız ve bağlı hibrit yenilenebilir enerji sistemi, Duyarlılık analizi.

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Finally, I would also like to extend my gratitude to my parents and sibling for their love and support. Without them, the completion of my research would not have been possible. Without forgetting I would like to remember another amazing person Raliya Hussein for being good friend and keeping me company throughout my master's degree.

Hussein Kerow Adan

23/07/2020

DECLARATION OF COMPLIANCE WITH MORAL PRINCIPLES AND RULES

I hereby honestly announce that this thesis is an unique work prepared by me; that I have acted according to the scientific moral principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be gained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "scientific plagiarism detection program" used by Anadolu University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my statement is detected in my work at any time, I hereby express my agreement to all the moral and legal consequences that are involved.

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(Signature)

Hussein Kerow Adan

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LIST OF ABBREVIATIONS

A	: Area of the Rotor Blade (m^2)
CCS	: Cycle Charging System
CO_2	: Carbon Dioxide
CO_2	: Carbon Dioxide
COE	: Cost of Energy
C_p	: Power Coefficient
CRF	: Capital Recovery Factor
DC	: Dispatch Strategy
DG	: Diesel Generator
EMRA	: Energy Market Regulatory Authority
FITs	: Feed-in-Tariffs
GHGs	: Greenhouse Gases
$\bar{G}_{T,STC}$	: Incident Radiation at Standard Test Condition [kWh/m2]
$\bar{G}_{T}$	: Solar Radiation
HOMER	: Hybrid Optimization Model for Multiple Energy Resources
HRES	: Hybrid Renewable Energy System
IPP	: Independent Power Producers
kW	: Kilo Watt
kWh	: Kilo Watt Hour
LFS	: Load Following Strategy
MW	: Mega Watt
MWh	: Mega Watt Hour
NASA	: National Aeronautics and Space Administration
NASA	: National Aeronautics and Space Administration
NPC	: Net Present Cost
NREL	: National Renewable Energy Laboratory
O&M	: Operation and Maintenance
PV	: Photovoltaic
R_{proj}	: Project Life Time
RF	: Renewable Fraction
RF	: Renewable Fraction

SOC	: State of Charge
STC	: Standard Test Conditions
TAC	: Total Annualized Cost
T_C	: PV Cell Temperature in Current Time Step [^{0}c]
TSR	: Tip Speed Ratio
V	: Average Wind Speed (m/s)
WT	: Wind Turbine
YEKA	: Yenilenebilir Enerji Kaynak Alanı
λ	: Tip Speed Ratio
ρ	: Air Density (kg/m^3)

1. INTRODUCTION

In this era of 21'st century, energy demand is high due to population increase and urbanization. The main challenge is to meet this expanding energy demand without interfering with the resources of the future descendants. In the previous decade, temperature has increased leading to debates on global warming between countries and scientists. By the end of this century an increase of 3-6^{o}C is expected [1]. The major cause being the population growth and rapid industrialization leading to increase in energy demand. The high energy demand is met through the fossil fuels. This conventional source releases greenhouse gases which is harmful to the atmosphere [1].

By 2040 world energy demand is anticipated to increase by 2.3% each year and 80% increase from its present value [2]. For us to meet this high demand of energy, the share of renewable energy sources (REs) needs to be increased. Therefore, renewable energy is considered a good alternative to conventional sources because they are ever-present (available everywhere), plentiful, Free, clean and environmentally friendly, hence reduces pollution and promotes sustainability a nation [3].

Since renewable energy is free and inexhaustible, the cost is stable, as compared to fossil fuel [4]. The potential of REs is enough to fulfil the energy demand of the entire world and it is well distributed across the universe unlike fossil fuels [5]. Also, electricity is generated from numerous sources such hydro power, nuclear energy, wind energy, solar energy, thermal energy, etc. these sources are assembled into infinite and finite energy sources. Finite energy is unlimited and naturally re-forming while infinite energy is unrecoverable once exhausted. Choosing the preferred renewable energy relies on factors such as; availability of resource, generation cost and eco-friendly.

Nevertheless, major challenge of renewable energy is that they are intermittent meaning they highly dependent on weather leading to continuous changing energy generation. For example, wind doesn't always blow and the sun doesn't always shine, which alters the consistency and safety of power supply. They also have high initial capital cost. To overcome this problem, renewable sources should be integrated with the conventional sources by using the strength of one source to stabilize the weakness of the other. This will make the hybrid renewable energy system (HRES) more dependable and less costly than system that rely on a single source of energy and maintains the continuity of power supply [6]. HRES uses different energy sources (renewable energy, diesel generator, grid) to supply the load demand. The most important advantages of a hybrid energy system are reliability, price reduction, efficiency improvement and less air pollutant when comparing to standalone renewable system [7]. Recently, hybrid renewable energy usage is becoming popular as a substitute to fossil fuel [6]. Hybrid renewable system with a diesel generator or grid as an alternate source can provide such a reliable power supply and reduce pollution. Standalone HRES is ideal for the case of remote places where extension of the grid is too expensive and the cost of energy from the diesel generators are also expensive when compared to the grid electricity which the village people cannot afford [8].

Figure 1.1. demonstrates typical hybrid renewable energy system that has a solar panel, wind turbine which acts as a main source of energy and a diesel genset as a backup energy while battery is utilized as an energy storage.

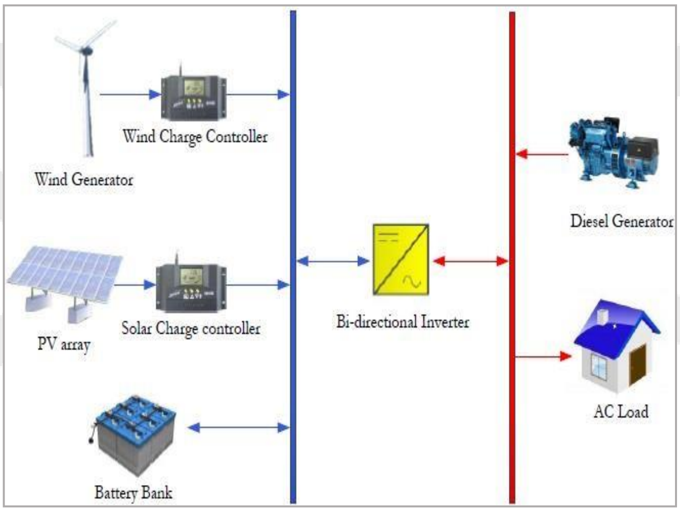


Figure 1.1. *Hybrid renewable energy system*

The major challenge of hybrid energy system is to come up with the optimal size and configuration of the system to supply the load demand at lowest cost and achieve economically attractive system [5]. To achieve this, proper selection of energy sources and component depending on the user demand is vital to have economical system. the proper selection is achieved by performing complete technical and economic evaluation of the hybrid configurations according to how available the renewables are through the whole year [8].

Since there are almost no literature studies comparing the technical and economic evaluation of a standalone and grid interactive HRES, because mostly they only concentrate on one, it is important to fill that gap. Therefore, the thesis focuses on the technical and economic evaluation as well as environmental impact of hybrid energy system with or without the utility grid using HOMER program to find the most economical as well as environmentally friendly system to supply power to an Electrical and Electronics Engineering Department in Eskişehir Technical University. The financial and environmental impacts such as the cost of electricity

(COE), net present cost (NPC), internal rate of return (IRR), renewable fraction, and CO_2 emission are analysed. The traditional opinion that solar energy is more costly than electricity from the utility grid is being defied by the solar panel cost reduction and the rising cost of fossil fuels. Due to fossil fuels diminishing, there is a high probability their price will rise in the future. This will further increase the cost of grid electricity and hence making the renewable energy cheaper [7], [9].

Households receive electricity from the utility grid at a cost pre-arranged in feed-in tariff. However, power cuts occur because of less generation capacity. Furthermore, as fossil fuel cost increases, the electricity cost will also increase leading to consumer dissatisfaction. Finally, clients may to shift to renewable energy to meet their needs. But, investing in solar power needs in advance capital. The financial profit has to be justified in order to persuade the client to make the initial payment.

The benefits of hybrid renewable energy are:

(i) Customers gets continuous power source

(ii) The hybrid system has a better return on investment

(iii) Less reliance on the utility grid,

(iv) Less operation hours of polluting diesel genset

(v) It has low maintenance and no need to buy fuel frequently compared to diesel genset system

(vi) Only one-time initial capital is required.

(vii) Protects customers from the ever-raising cost of grid electricity tariffs.

Renewable energy is the only energy source less affected by Covid-19 pandemic. The demand for other sources has decreased, renewable electricity continues to increase. For example, in the first quarter of 2020 global renewable energy usage has increased by 1.5% compared to the first quarter of 2019. Electricity generation from renewable energy has also increased by 3% due to completion of new wind and solar projects within last year and because renewables are dispatched faster than other sources. The share of renewable energy in global energy generation has risen from 26% during the first quarter of 2019 to 28% in the same quarter in 2020. This increase is because of decline demand in coal and gas, but still two of them represent 60% of global electricity generation share [10].

1.1. Literature Review

Several researches are been done to study the technical and economic evaluation of hybrid energy systems. Some of them are listed below:

Usman et al. [1] conducted a technical and economic evaluation of PV/diesel genset/ on grid hybrid system using HOMER program to supply power to an institution of Engineering in

New Delhi/India. The result showed that, PV/grid connected configuration was the most economical one with least COE of 0.12 $/kWh. This is the same as the cost of grid electricity but with time grid price is expected to increase, hence making PV/grid connected system more economical.

Abed et al. [4] performed technical and economic estimation of HRES located in a remote area of Egypt. HOMER program was used to get an optimal configuration based on NPC and COE. They found that a hybrid energy system which consists of 10 kW solar panel, 7.5 kW wind turbine, 2.8 kW diesel genset and 20 battery banks (360 Ah) supplied power to the study area. The NPC and COE of the system was $113,256 and 0.179$/kWh respectively, hence PV/wind/diesel genset/battery hybrid system is regarded as the most economical and less pollutant.

Asrari et al. [6] assessed the feasibility of adding a renewable source to a village in Iran that was powered by diesel generator and connected to the grid using HOMER software. Firstly, the paper examines how economical it would be to supply the village with the diesel genset and add renewable resources. At the same time, they explored how the renewable energy resources can be combined with the utility grid to achieve an inexpensive and eco-friendly hybrid system. The result showed that combination of renewable energy to the diesel only system before and after the arrival of the grid could have lowered the expenses and reduced emissions.

Kolhe et al. [7] Considered technical and economic evaluation of diverse hybrid renewable system using HOMER pro program to achieve an optimum configuration to supply power to a remote in Sri Lanka. PV/WT/DG/battery having 20 kW solar panel, a wind turbine of 40 kW, diesel genset of 20 kW and battery bank of 40 was found as the most economical hybrid configuration and supplied power with 0.36 $/kWh COE. The energy price was more expensive than the price of the grid price in Sri Lanka but due to lack of utility grid in the study area, the hybrid system would improve the rural lifestyle and reduce greenhouse gas emissions.

Anene et at. [8] examined the technical and economic evaluation to test the importance of a standalone HRES to a rural area in Nigeria since hybrid systems uses renewable energy sources and conventional sources as a backup, making the system reliable and reduce cost power for villagers. Their aim is to present the finest configuration of a hybrid system to supply power to a village in Abuja, Nigeria. HOMER pro program was used to perform simulations for several system configurations. The simulation results revealed that the most economical configuration is the PV/diesel generator/battery system. The system had COE of 0.50 $/kWh, NPC of $390,914 and 45% RF compared to the diesel only system with COE of 0.682 $/kWh, NPC of $533,034.

Baneshi and Hadianfard [11] analysed the technical and economic variables of PV/wind/battery/diesel hybrid power system for a huge electricity consumer in Iran. HOMER pro program was used to find out the feasibility of the hybrid system to satisfy the load demand of the large electricity consumer and the program is able to identify the optimal configuration in terms of technical, economic and environmental impact. Both standalone and grid interactive systems were studied. Results display that for standalone system the electricity cost of 0.093–0.126 $/kWh and renewable fraction of 43.9% was obtained while grid interactive system without battery bank had COE of 0.057–0.084 $/kWh and RF of 53%, respectively. Here, grid interactive hybrid system is the most economical one with good RF leading to less pollution.

Gebrehiwot et at. [12] studied the impact of hybrid system on a rural village in Ethiopia using HOMER pro program because hybrid system integrates several energy sources to reduce reliability on one energy sources and optimize production cost. HOMER is able to come up with the less economical system for the village's load demand. The results revealed that the hybrid configuration of PV/WT/DG/battery is the best economical system. The energy cost of the system is projected at 0.207 $/kWh and NPC of $82,734. The most economical configuration is able to minimise carbon dioxide emissions to 37.3 tons per year in comparison with to diesel only system. this shows that the hybrid system is a best system for rural villages.

Kumar et al. [13] assessed the technical and economic calculation of standalone hybrid renewable system to electrify a remote village using HOMER pro program. The results revealed that the hybrid off grid system has less electricity cost and more reliable in comparison with the PV or wind power system. Therefore, the best optimal system for the village would be the hybrid renewable system. HOMER's optimization results exhibited that the most ideal configuration is the PV/Wind/diesel/battery system which can supply electricity at a cost of 0.201 $/kWh, NPC of $270,781 and 44% RF. For the case 100% renewable fraction, the PV/battery system would be attractive in terms of environmental protection but it has higher power cost of 0.299$/kWh and NPC of $286,166.

Hatem & Mabrouk [14] performed technical and economic assessment of PV/Wind/Battery/Grid hybrid system using HOMER software to electrify an institution of Research and Technology in Tunisia. The results presented NPC and COE of $ 44,705 and 0,224$/kWh and a maximum RF of 78%, but after considering sensitivity analysis based on the speed of wind, global solar insolation, cost of grid power and sellback cost. PV/grid hybrid system turned out to be the most economical configuration with $27,986 NPC and 0.140 $/kWh COE.

Yadav et al. [15] used HOMER software to perform the technical and economic evaluation of PV/WT/DG/battery hybrid configuration for a remote telecom station in Darbhanga city, India. After the simulation, they realized that PV/wind/diesel genset/battery was the most economical system with 0.210 $/kWh COE while PV/diesel genset had the maximum energy cost of 0.709$/kWh.

Ghasemi et al. [16] analysed technical and economic study of standalone PV/diesel Genset/battery hybrid system to provide power to a remote area in Eastern part of Iran. They used HOMER program for simulation purposes. The system's NPC, RF and air pollutant were used as a criterion to determine the most viable system. The program indicated that a standalone HRES with 15 kW solar panel, 20kW diesel genset and 20kW inverter was the cost-effective system with NPC, COE and renewable fraction of $309,034, 0.464$/kWh and 30%, but adding 10 of batteries to the system diminishes the total NPC to $286,315 and COE to 0.430 $/kWh but rises the RF to 35% making it more feasible. They finally concluded that PV/diesel genset/battery hybrid configuration is not only economical but also a perfect candidate to provide power to rural areas in Iran.

Mondal et al. [17] conducted HOMER simulation to determine the potential of hybrid energy system to provide power to a remote village in Ethiopia with lowest cost of energy and by comparing it with diesel only system. The researchers learnt that PV/WT/DG/battery configuration had the least NPC and COE of $82,734 and 0.207 $/kWh respectively. The system cuts 37.3 tons of CO_2 emissions in comparison to diesel genset system, hence renewable hybrid energy system is considered the best system for remote areas.

Khalid et al. [18] evaluated technical and economic study of two different hybrid renewable energy systems using HOMER program. The results specified that hybrid energy system that used battery as energy storage was cost effective with NPC of $ 581,916 and COE of 0.359 $/kWh while the system that used hydrogen as energy storage was eco-friendly but not cost effective with NPC of $ 603,856 and COE of 0.373 $/kWh. The system that used hydrogen was the best system from the for environmental point of view due to lack of emissions.

1.2. Objective of the Thesis

The aim of the thesis is to examine the technical and economic evaluation as well as environmental impacts of various hybrid renewable energy system with or without the utility grid using HOMER software to find the most economical and eco-friendly hybrid system for the Electrical and Electronics Engineering Department in Eskişehir Technical University. By doing the two simulation at the same time, customers will have choices depending on their interest whether its economical or environmental concern, also the thesis encourages the use of hybrid renewable energy for government, commercial and residential buildings in Turkey.

1.3. Outline of the Thesis

The sections of the thesis are prepared as follows: section I describes the introduction and literature review. Section II explains the methodology. Section III shows the results and discussion and in section VI, conclusion is presented.

2. RENEWABLE ENERGY POTENTIAL OF TURKEY

2.1. Solar Energy Potential

The daily solar insulation received on a clear day around noon is around 1000 W/m^2. This insulation is typically measured in kWh/m^2. For example, the solar resource that is available for 5 hours a day on average can be calculated by equation 2.1.

$$\frac{5 \times 8760}{24} = 1{,}825 \frac{kWh}{m^2} / year \tag{2.1}$$

Turkey is a country located along latitude of 38.9^{0}N and longitude of 35.2^{0}E. The country's solar energy potential is higher than most places in Europe behind Spain. The average daily sunshine is 7.2 hours and the yearly solar insulation is 1,533 kWh/m^2/year equivalent to 4.2 kWh/m^2/day, which is higher than most parts of Europe. Figure 2.1. shows solar energy potential of Turkey. The South Eastern Anatolia and Mediterranean parts are the areas with highest solar energy potential [19, 20].

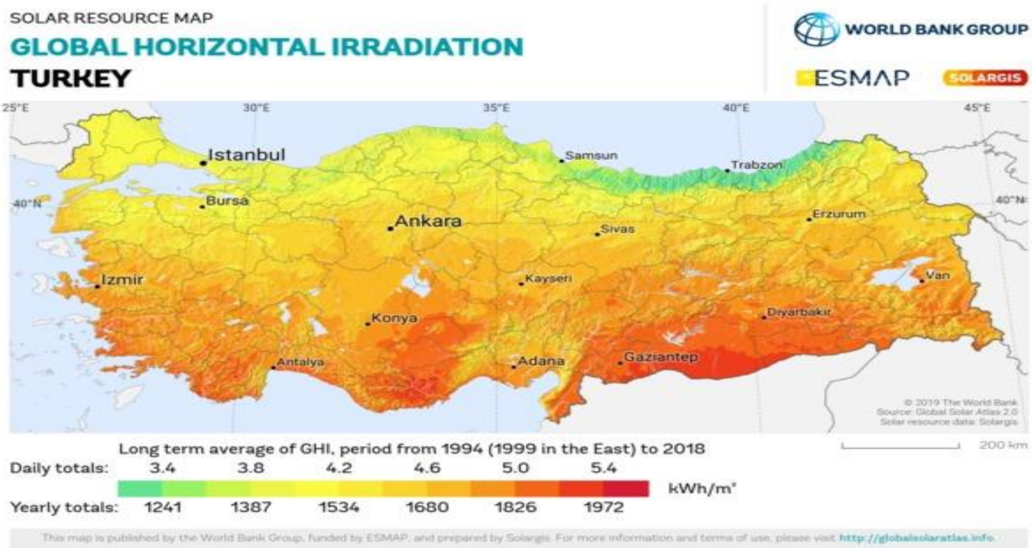


Figure 2.1. *Global horizontal irradiation*

Turkey has over 6 GW of solar power plant in operation. Still this capacity is small compared to the 91.3 GW of Turkey's installed power [21].

Figure 2.2. shows that, Turkey's installed renewable energy has increased from 16.20% in 2018 to 17.72% at the end of 2019 and at the same time the share of fossil fuel has decreased. This shows that Turkey is committed to sustainable energy in the future [18]. Government promises to rise the renewable resources in the power mixture by introducing feed-in tariff for both solar and wind because the country generates half of its energy from imported gas and coal [22].

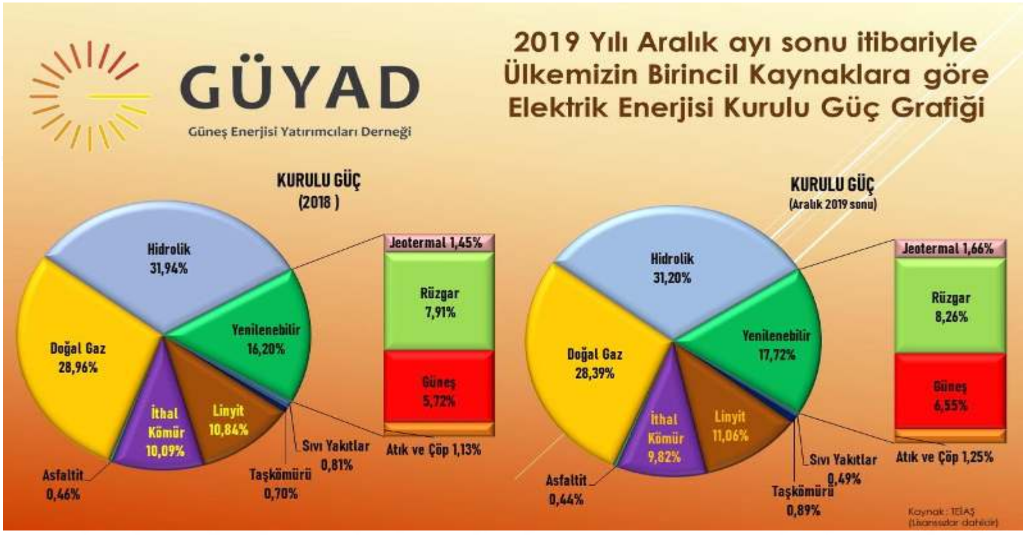


Figure 2.2. *Turkey's installed electricity capacity share*

2.2. Wind Energy Potential

Wind is caused by the solar energy; air movement is caused by the earth surface getting heated at different time. Roughly 2% of the solar power reaching the ground is transformed to wind power [23]. Wind power has some advantages and disadvantages:

They are renewable, clean, eco-friendly but also has high initial cost and variable energy production. With this information, it is clear that electricity from wind energy is much cleaner and more economical than fossil fuels [2].

Wind turbine is able to generate energy at a specific wind speed. For example, the cut-in speed of a wind turbine is between 2-4 m/s, the nominal speed is between 10-15 m/s and the cut-out speed is between 25-35 m/s. Each wind turbine reaches its highest power generation at a specific wind speed known as cut-out speed after which the turbine automatically stops to ensure the system is not damaged [23].

In Turkey, 50 m above the ground level and wind speed of over 7.5 m/s, 5 MW of wind power plants can be installed per km areas. According to Turkey's State Meteorological Studies, the country has an annual average wind speed of 2.58 m/s and wind power density of 25.82 W/m^2. The maximum wind energy in Turkey is experienced at western coasts. As can be seen from Figure 2.3. Marmara region has the highest wind speed, followed by Southeast Anatolia and the Aegean region. These regions are extremely appropriate for wind power generation, because the wind speed surpasses 3 m/s in most of these regions [24].

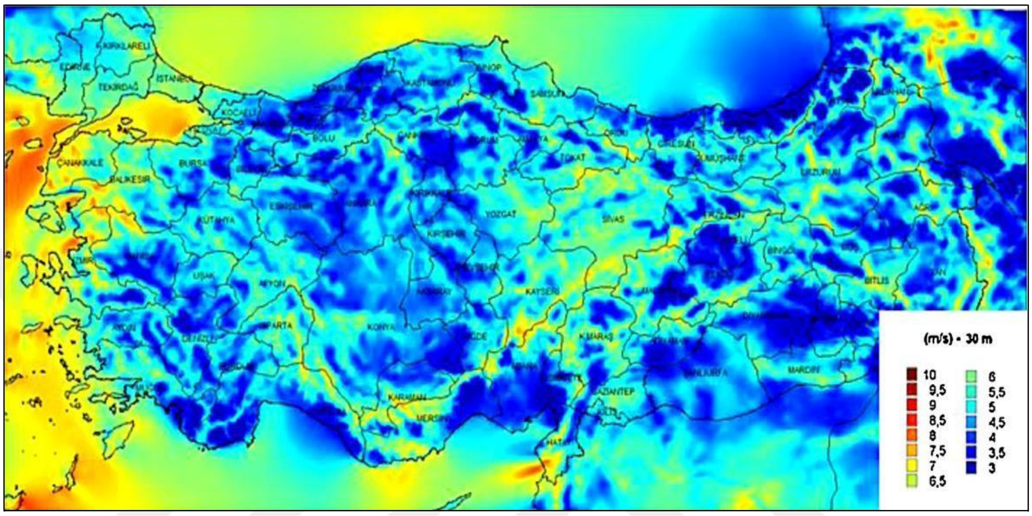


Figure 2.3. *Wind velocity distribution in 30 m high in Turkey*

Turkey's wind energy potential has been estimated to be 48 GW. An onshore wind potential of 37 GW and a completely untapped offshore wind potential of 11 GW. Turkey has large potential of wind, but the cumulative installed power capacity is 7.6 GW as of January 2020 [2] as seen in the Figure 2.4.

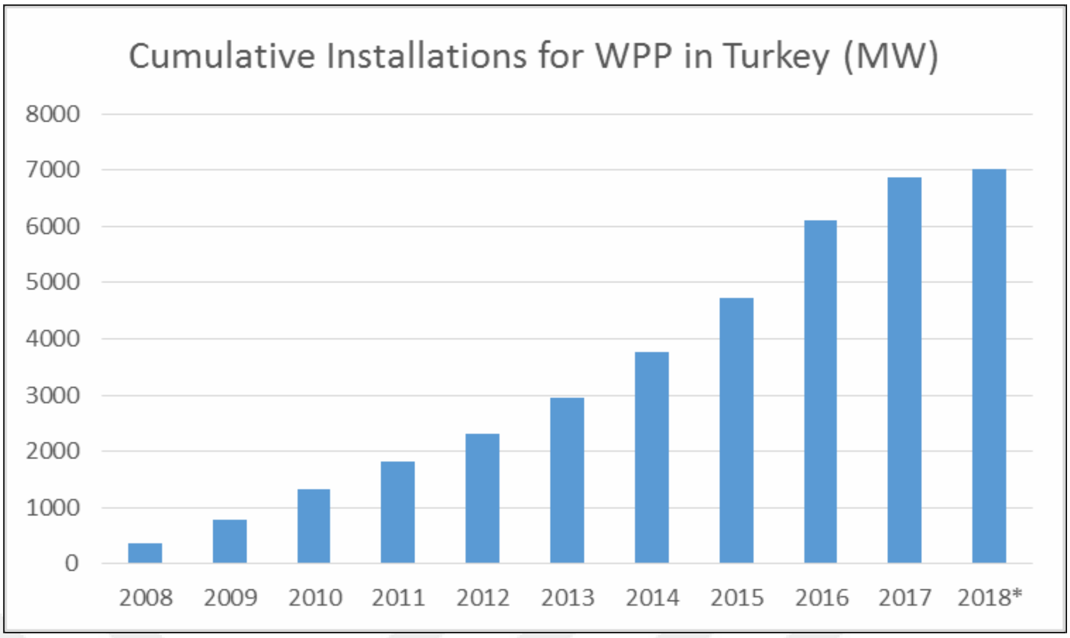


Figure 2.4. *Wind power plants increasing installations in Turkey (MW)*

Today, approximately 8.91% of Turkey's energy consumption comes from wind power. The first wind power plant was established in çeşme with a capacity of 55 kW. Since the beginning of 2000, the installation of wind power plants has increased and still growing. The annual growth of wind power plants installation in Turkey is shown in the figure 2.5 [2].

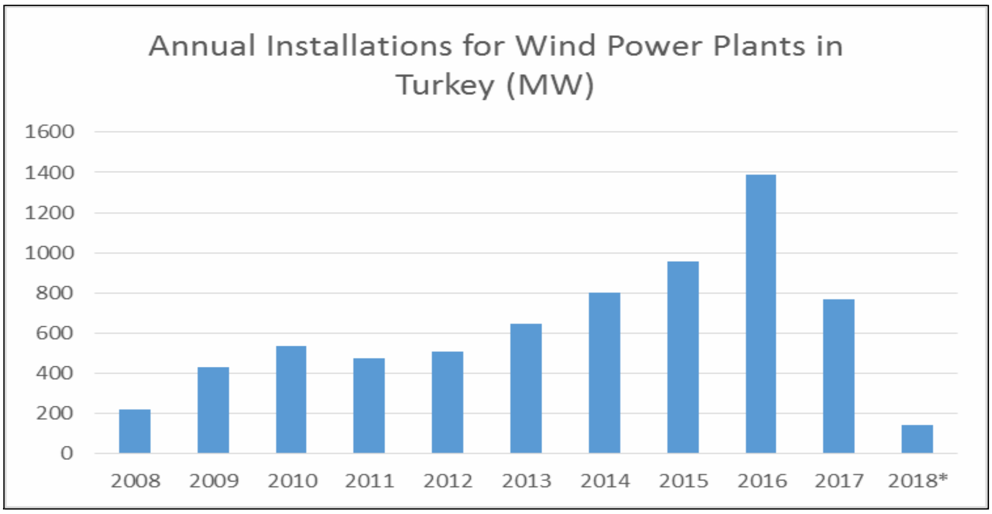


Figure 2.5. *Wind power plants yearly installations in Turkey (MW)*

Turkey's wind energy potential over numerous regions are listed in Table 2.1. The Marmara region is the region with the highest wind speed with value of 3.29 m/s, followed by Aegean and Southeast Anatolia. Therefore, wind power plants are mainly installed in these regions.

Table 2.1. *Turkey's wind energy potential over different areas*

Region	Yearly wind density (W/m^2)	Yearly wind speed (m/s)
Eastern Anatolia region	13.19	2.12
Middle Anatolia region	20.14	2.46
Black Sea region	21.31	2.38
Mediterranean region	21.36	2.45
Aegean region	23.47	2.65
South-Eastern Anatolia region	29.33	2.69
Marmara region	51.91	3.29
Average	**25.82**	**2.58**

According to Turkey's meteorological studies, the annual wind speed is 2.58 m/s and wind power density is 25.82 W/m^2. Operational wind power plants according to the regions in Turkey is shown in Figure 2.6. [2].

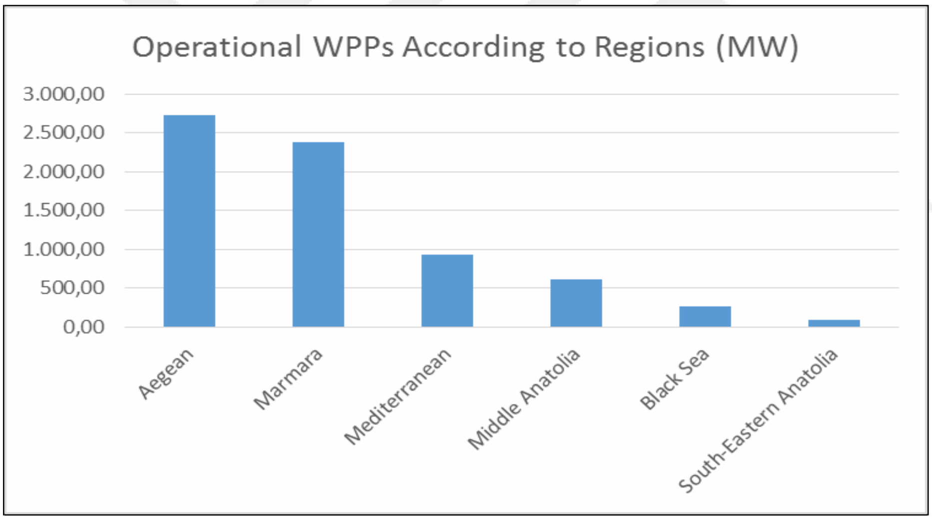


Figure 2.6. *Functioning wind power plants according to regions (MW)*

2.3. Renewable Energy Outlook of Turkey

Turkey's energy demand has been increasing due to economic and population growth. According to the data from the Ministry of Energy and Natural Resources, energy demand of Turkey will increase approximately by 7 percent each year until 2023 and the Government plans to rise the share of renewable energy up to %30 to meet the demand. Some of the targets of the Turkish government for renewables by 2023 are:

- Increasing energy efficiency
- Ensuring energy supply security
- Increasing the fight against climate change

- expanding the renewables energy share to 30%
- adopting the usage of hydropower as energy generation
- expanding the capacity of geothermal power to 5,000 MW
- Increasing the installed capacity of solar power to 5,000 MW
- Increasing the capacity of wind power to 20,000 MW

And when these objectives are achieved, Turkey's energy future will move forward with more robust steps [2].

Turkey's installed energy capacity in 2018 was 88.5 GW and in the beginning of 2020, it has reached 91.34 GW. Natural gas provided 28.32% of total installed power, 21.28% by coal, 31.20% by hydropower, 8.36% by wind power, 1.66% by geothermal, 6.67% solar energy and 2.52% from additional sources.

Figure 2.7. shows the electricity share of Turkey from different sources. The majority of the capacity additions in Turkey have been realized in the last 15 years as a result of the investments made by the private sector. In 2019, EUAS (State Electricity Generating Company) provided 18.6% of total installed energy capacity of Turkey, the private sector with 73%, the build-operate plants with 4.8%, build-operate-transfer plants with 0.4% and unlicensed power plants with 3.1% [25]. Turkey encourages the private sector to spend in renewable energy through feed-in-tariffs.

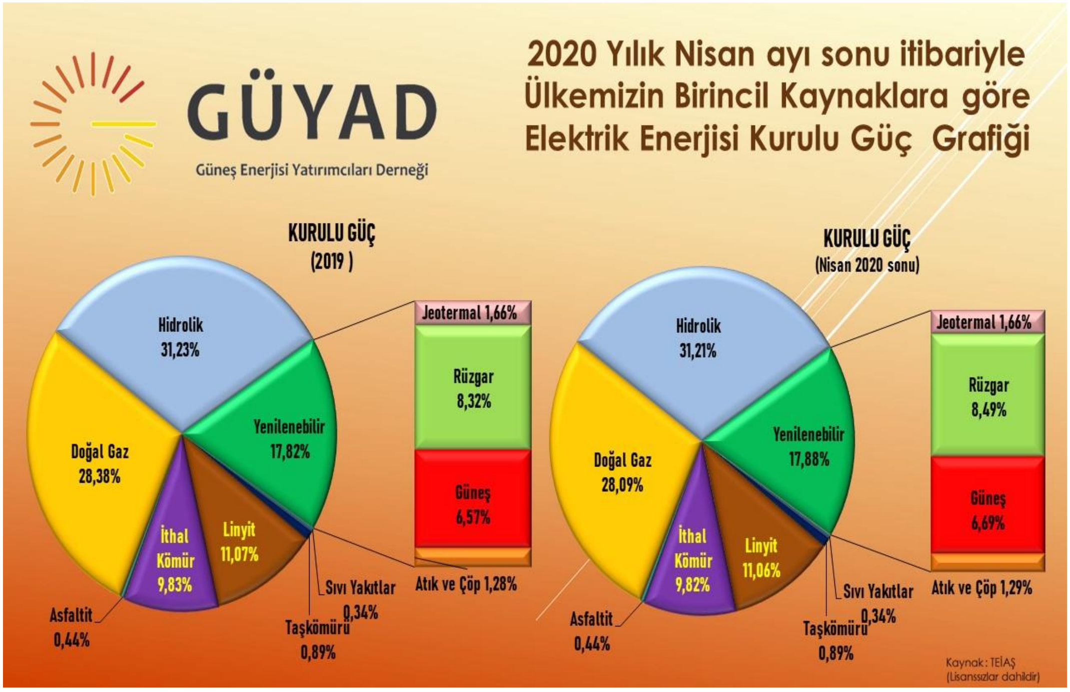


Figure 2.7. *Electricity share of Turkey from different energy sources*

2.4. Feed-In Tariff

The promotion of renewable energy in Turkey's is done through Feed-in tariff. The Government top priority is to decrease its import dependency by utilizing its renewable energy potential. The YEK-Law distinguishes the amount of the tight feed-in-tariffs depending on technology and whether the plant components were produced in Turkey or not [26]. Table 2.2. shows Turkey's feed-in tariff for different renewable energy sources.

Table 2.2. *Feed-in tariff*

Renewable sources	Feed-in tariff
Wind energy	❖ Feed-in tariff: $7.3 cent/kWh on- and off-shore. ❖ Local-content bonus: $0.6-3.7 cent/kWh.
Solar energy	❖ Feed-in tariff: $13.3 cent/kWh ❖ Local-content bonus: $0.6-6.7 cent/kWh
Geothermal energy	❖ Feed-in tariff: $10.5 cent/kWh ❖ Local-content bonus: $0.7-2.7 cent/kWh
Biogas	❖ Feed-in tariff: $13.3 cent/kWh ❖ Local-content bonus: $0.4-3.8 cent/kWh
Hydro-power	❖ Feed-in tariff: $7.3 cent/kWh ❖ Local-content bonus: $1-2.3 cent/kWh
Biomass	❖ Feed-in tariff: $13.3 cent/kWh ❖ Local-content bonus: $0.4-1.8 cent/kWh

Because of feed-in-tariff, Turkey's renewable energy production has improved from 12.73% in 2018 to 16.33% in March 2020 and the total installed renewable capacity has also improved from 16.20% in 2018 to 17.97% in March 2020. Similarly, the share of fossil fuels has decreased. This shows that Turkey is committed to sustainable energy in the future [21].

Turkey aims to produce its own energy since the country's energy demand and population is increasing every year, making it vulnerable and lose substantial amount of money through importation of fossil fuel. Hence switching to renewable power is a good idea since it helps the country reach its vital goals specified in the development action plans such as: sustainable development, avoiding energy import and increasing energy security [2].

It is predicted that Turkey's electricity consumption will double by 2023, therefore the country targets a 30% share of renewable energy in power generation by 2023. The aim is to reach 34 GW of hydropower, 20 GW wind energy, 5 GW solar energy, 1 GW geothermal energy and 1 GW biomass. In addition to this, Turkey is the world's 17th and Europe's 6th largest economy and wants to be the world's 10th largest economy [19]. For this to be possible the country has to invest more in renewable energy particularly solar and wind energy.

The Paris agreement that was held in 2015 had the aim of restricting the global temperature increase below 2^0C. As of February 2020, 194 states and the European union have signed. 188 states and the European union representing more than 87% of global greenhouse gas emissions have ratified the agreement including china and the United States and India with a total of 42%. Turkey has signed the 2015 Paris treaty but it is yet to approve, although the country is committed to reduction of CO_2 from its energy sector [27].

2.5. Global Renewable Energy Outlook

Towards the end of 2018, the projected portion of renewable energy in the global electricity generation was more than 26%. But now it responsible for one-third of global installed power capacity, because of the policy initiatives set by Governments, the decreasing costs of renewable energy components and technological advancements [28].

Despite the increase in renewable energy capacity additions each year, the world is not yet on its pathway to meet the goals of Paris agreements since greenhouse gases emissions has increased by 1.7% in 2018 because of large consumption of fossil fuels. The problem is that the fossil fuel companies spend hundreds of dollars to stop climate change policies and ads that can impact public view [28].

By the end of 2019, global installed renewable energy capacity accounted for 2,537 GW with hydropower responsible for 1,190 GW. Wind and solar energy followed with capacities of 623 GW and 586 GW respectively. Other renewables were 124 GW of bioenergy and 14 GW of geothermal. Between 2019 and 2024, the power capacity will rise by 1,200 GW because of renewable's cost reduction and rigorous government policy. Solar PV will account for 60% of that growth as shown in Figure 2.8 [29].

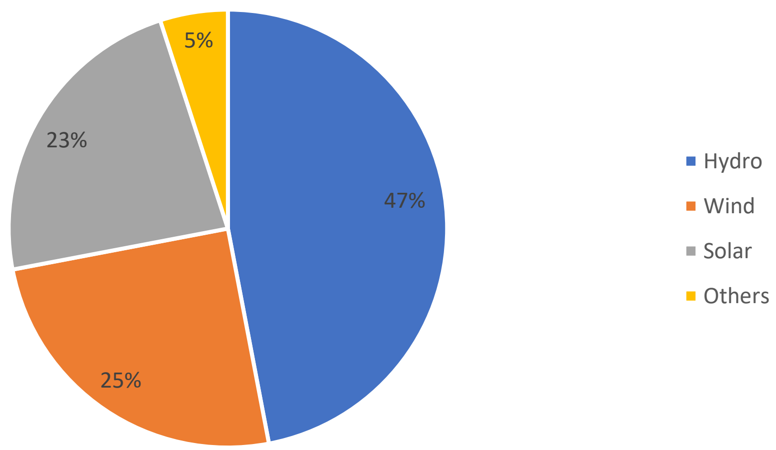


Figure 2.8. *Renewable energy capacity share by energy sources*

2.6. Renewable Energy Capacity Progress

Renewable energy capacity has increased by 176 GW in 2019. Solar and wind energy had the most renewable capacity addition in 2019 with 90%. This means that solar and wind energy are the two popular renewable energy resources. Figure 2.9. demonstrates it well.

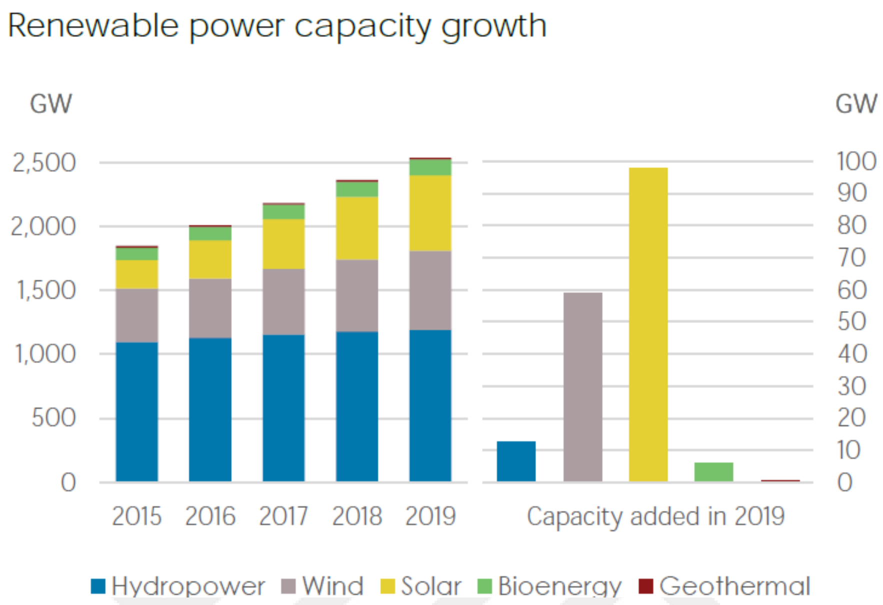


Figure 2.9. *Renewable energy capacity progress*

Figure 2.10. shows that in 2018, China' installed renewable capacity was 730 GW and in 2024, it is anticipated to reach 1,219 GW – making it the world's renewable power front-runner for the next five years, United States is second, in 2018 it had installed renewable capacity of 280 GW and its anticipated to reach 411 GW of installed renewable capacity. India is also expected to reach 235 GW in 2024. Germany is the fourth highest renewable energy leader having installed renewable capacity of 166 GW, followed by Brazil with 156 GW and Japan

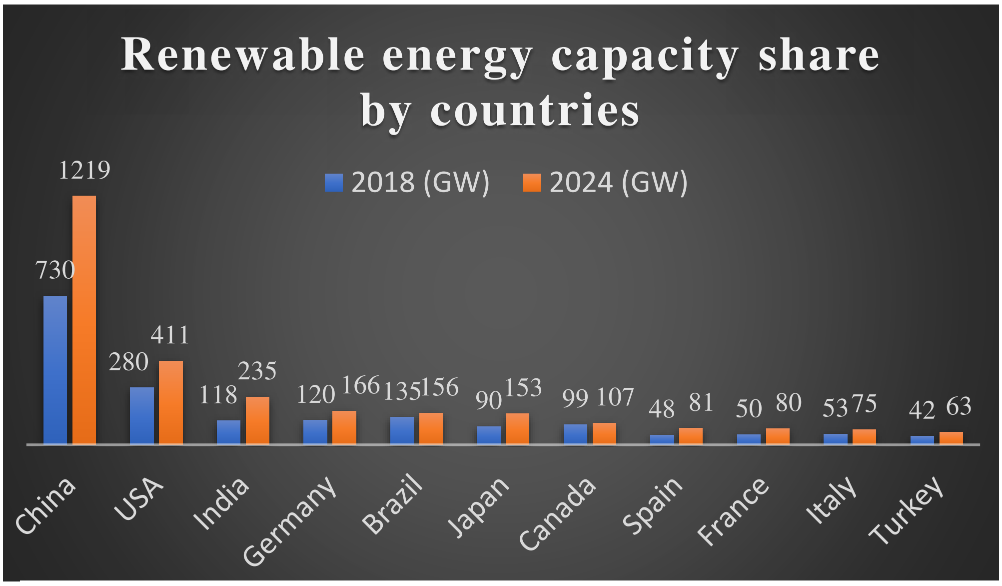


Figure 2.10. *Renewable energy capacity share by countries*

follows with 153 GW. Canada and Spain are expected to reach 107 GW and 81 GW, respectively in 2024. France with 80 GW while Italy is set to become the 10th country in the world with highest renewable energy capacity in 2024 [30].

By the end of 2018, Turkey had 42 GW of installed renewable capacity and as per the International energy agency (IEA), this is set expected reach 63 GW by 2024. This progress will make Turkey among the five countries in Europe and 11th in the world with the highest renewable energy capacity [30].

In the thesis, simulation of several hybrid renewable energy system with and without the grid is done using HOMER pro software to obtain the most cost effective and environmentally friendly hybrid energy system. The PV panel, wind turbine, generator and the grid act as the energy sources for HOMER program. Hybrid system has at least two and maximum of three energy sources, improving the reliability of the system. The combinations used are PV/WT/ /DG configuration, PV/DG/battery, WT/DG/battery, PV/WT/grid interactive, PV/grid interactive and WT/grid interactive.

3. METHODOLOGY

Modelling of renewable energy system is highly dependent on meteorological data and the load profile of a specific place, therefore a system relying only on one energy source can't provide a continuous power; to have a continuity of power, it is always good to rely on two or more energy sources. The thesis considers several different configurations of hybrid renewable energy system and compares them using HOMER pro program for simulation, optimization and sensitivity analysis.

3.1. HOMER Software

Hybrid optimization model for multiple energy resources (HOMER) program was initially established by national renewable energy laboratory (NREL) in the USA but now it is operated by Homer energy. It simulates a standalone and grid interactive energy system based on user inputs such as load profile, renewable sources, the component's technical and economic details. The program runs the simulations of all possible combinations and gives the results according to the most cost-effective ones which can meet the load demand by arranging them in terms of their NPC in ascending order. The system with the lowest NPC is the optimal hybrid configuration [5, 31].

The HOMER program uses mathematical calculation for simulation. The software simulates several numbers of situations. For example, integrating traditional energy sources with the renewables to satisfy load demand. Investigations can be either as grid integrated or standalone and their emissions levels studies. HOMER enables the user to make inputs of renewables according to their demand. This will let the user to investigate the potential of small-scale power systems before the final application. Also, it permits comparing several diverse configurations according to their technical and economic benefits [32].

HOMER designs hybrid energy system's physical components and the lifecycle cost, in turn lets the user to compare many diverse design selections, according to their technical and economic benefits. Also, the program helps in understanding the effects of uncertainty based on in the user inputs. The program chooses whether or not the renewable energy can supply the load demand. If the renewable sources are inadequate, it ensures that other sources such as generator or the grid operates and satisfy the demand [33].

Department of Electrical and Electronics Engineering in Eskişehir Technical University is used as a case study. Its daily energy consumption is approximately taken as 2 MWh. Both standalone and grid interactive hybrid system was considered to see the most economical and environmentally friendly one.

HOMER performs three main tasks: simulation, optimization and sensitivity analysis.

Simulation: HOMER simulates the performance of a specific hybrid system to identify the technical feasibility and economical cost for each hour of the year. The software also simulates the operations of a hybrid energy system for a whole year, in time steps from one minute to one hour.

Optimization: HOMER program simulates various system configurations at lowest cost. Also, it calculates the ideal value of the variables for which the user has control over, for example system's component size.

Sensitivity analysis: HOMER performs numerous optimizations under series of inputs to measure the effects of uncertainty. So, sensitivity study helps to establish the effect of uncertainty over which the program designer has no power to control, such as wind speed, solar insulation, price of fuels. Finally, the most economical hybrid configuration can be recognized based on the optimization result [34].

Figure 3.1. shows the connection between simulation, optimization & sensitivity analysis. optimization may contain one simulation or multiple simulation. While the sensitivity analysis also can contain multiple optimizations but for any given system, only one sensitivity analysis is likely. So, in this study, mixtures of renewable energy, diesel generator, battery and the grid are adopted to come up with the most optimal hybrid system design [35].

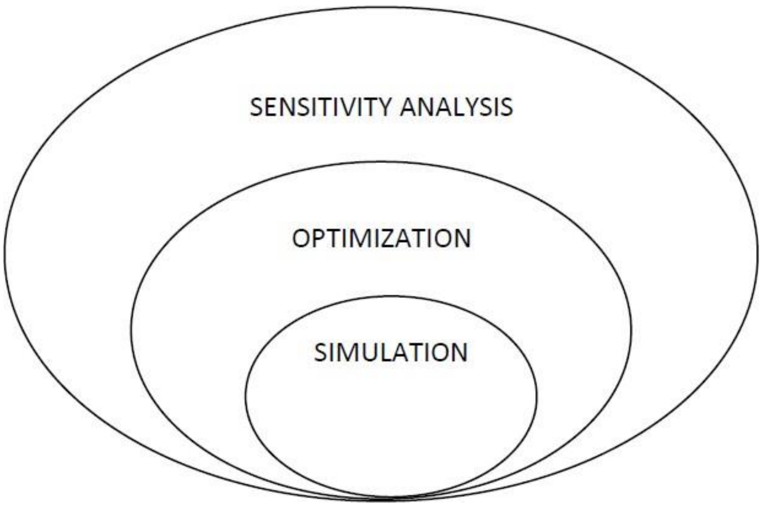


Figure 3.1. *Correlation between simulation, optimization, and sensitivity analysis*

3.2. Physical Modelling of Homer Software

The details about the physical function of HOMER pro is presented. The proposed system uses solar, wind, diesel genset and the grid. The study area for the system is Eskişehir climate with latitude of 39.70^0N and longitude of 30.5^0E. HOMER pro program was used to find the location of the study area from NASA's prediction of worldwide energy resources. The study area is shown in Figure 3.2.

Figure 3.2. *Location of the study area (source: google earth*)

3.3. Load Profile

Electrical and Electronics Engineering Department in Eskişehir Technical University is used as a case study. The average electrical load for the Department was taken approximately as 2MWh/day. Grid interactive and a standalone hybrid configuration is designed by HOMER program to compare their technical, economic and pollution results. Figure 3.3. shows the daily, monthly and yearly load profile. The maximum energy demand is experienced in the months of June, July, August and September. While, November, December and January have the lowest load demand.

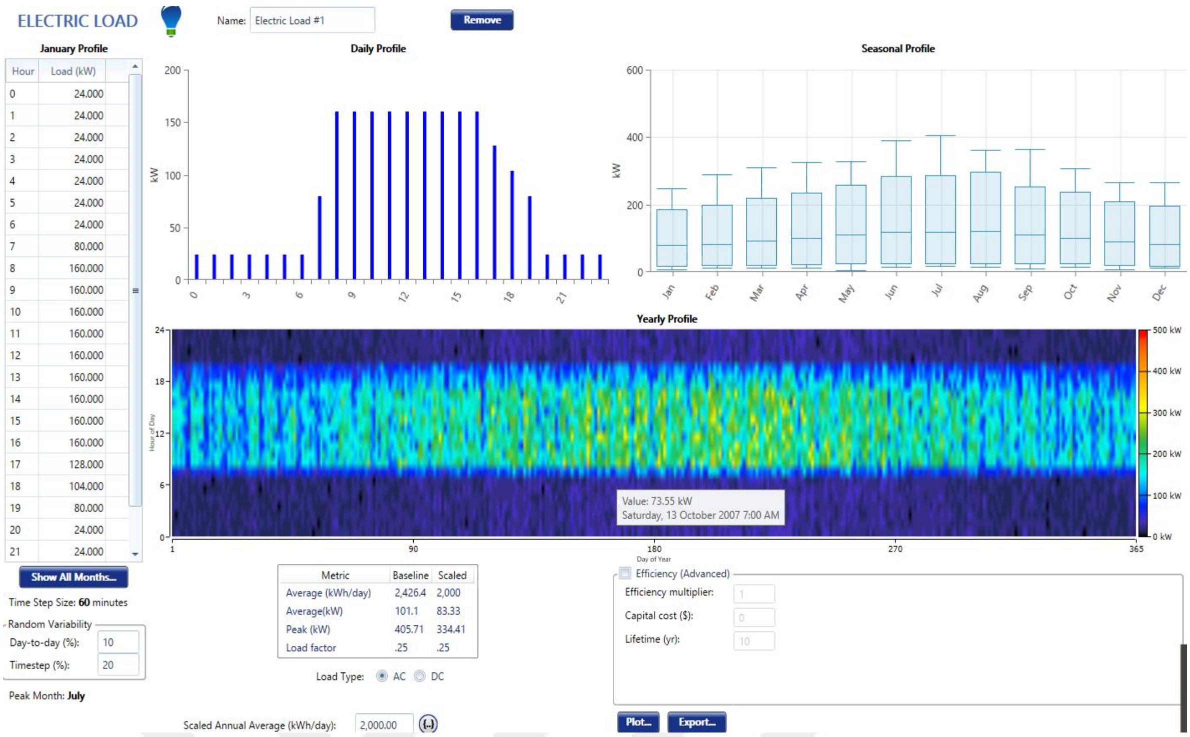


Figure 3.3. *Load profile for the study area*

3.4. Available Renewable Energy Resources

The renewable energy considered are solar and wind energy. Their technical and economic specifications are presented.

3.4.1. Solar energy

The solar irradiance was attained from NASA surface meteorology. The yearly average solar insulation for Eskişehir region is 4.26 kWh/m^2/day. Table 3.1. shows the monthly solar irradiance and clearness index values. Clearness index is a dimensionless number between 0 and 1 and it's the degree of the clarity of the atmosphere. Figure3.4. shows that the highest solar irradiance is experienced in June, July and August while the lowest is in November, December and January [4].

Table 3.1. *Solar data from HOMER*

Month	Clearness index	Average daily insulation ($kWh/m^2/d$)	Average temperature(^0C)
January	0.442	1.890	0.790
February	0.465	2.640	1.440
March	0.499	3.820	4.730
April	0.479	4.620	10.310
May	0.536	5.910	15.470
June	0.587	6.80	19.270
July	0.626	7.060	21.990
August	0.619	6.270	21.780
September	0.605	5.030	18.250
October	0.538	3.360	12.720
November	0.480	2.200	6.600
December	0.405	1.560	2.230

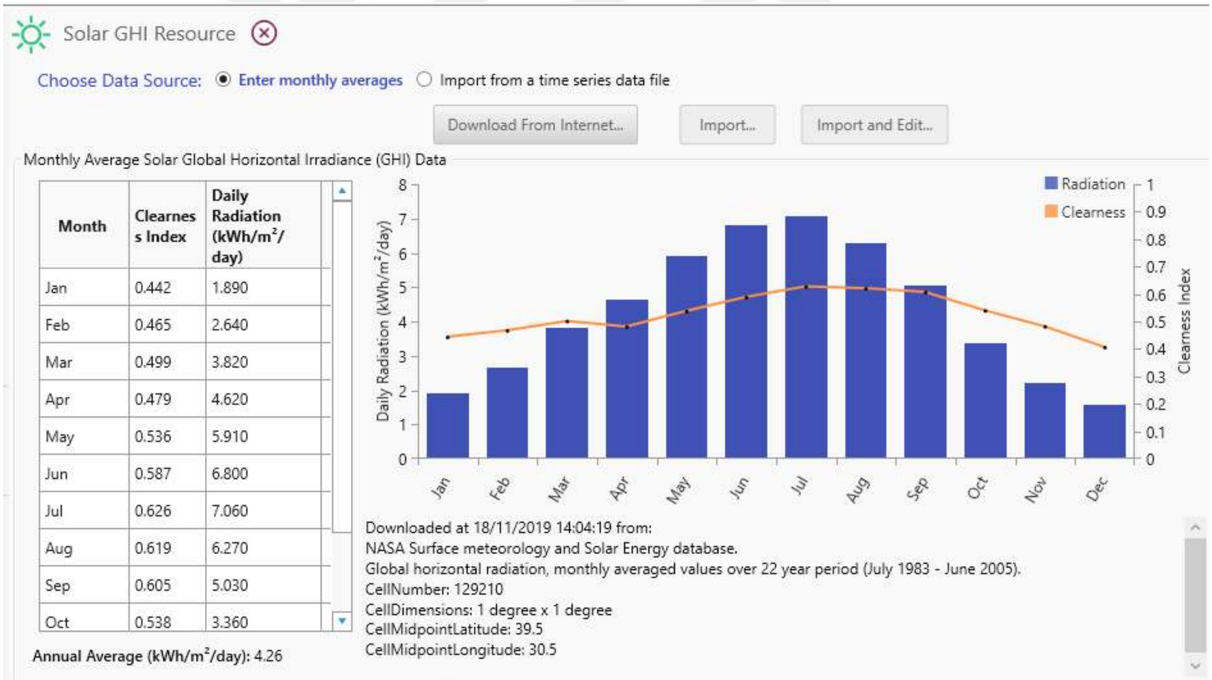


Figure 3.4. *Monthly solar insulation and clearness index for Eskişehir*

Solar power classification according to the total solar radiation is given in Table 3.2. The study location has a yearly solar irradiance of 1555 kWh/m^2, which means it has a fair solar energy potential, making the area suitable for small scale solar projects.

Table 3.2. *Classification of solar power*

Class of solar energy	Potential	solar insulation (kWh/m^2/year)
1	outstanding	>1850
2	Great	1750-1850
3	Fair	1400-1750
4	poor	<1400

3.4.2. Wind energy

The wind data is downloaded from NASA surface meteorology. Figure 3.5. shows that the highest wind speed is experienced in the months of February and lowest in May. The average annual wind speed for Eskişehir region is 4.76 m/s. In winter the wind speed is high while in summer it is low which is the opposite of the solar insolation, this implies that solar and wind energy assist each other [4].

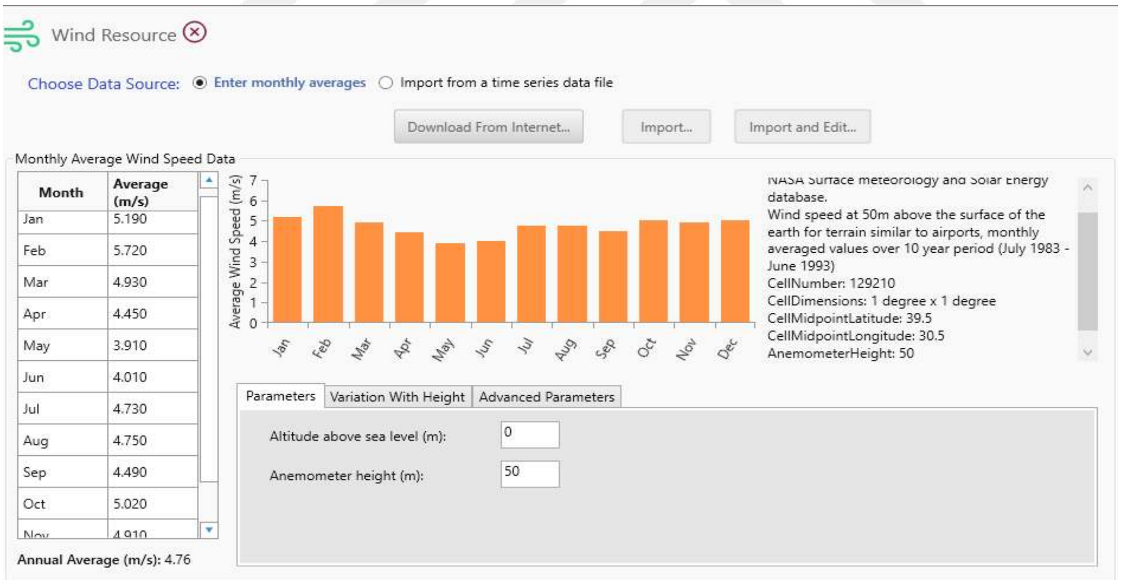


Figure 3.5. *Monthly average wind speed data for Eskişehir*

The wind energy is separated into 7 classes according to wind speed and wind power density as shown in Table 3.3 [36, 37].

Table 3.3. *Classification of wind power*

classes of Wind power	Potential	Density of Wind power (W/m^2)	Average wind speed (m/s)
1	Poor	<100	4.4
2	Marginal	100-150	5.1
3	Moderate	150-200	5.6
4	Great	200-250	6
5	outstanding	250-300	6.4
6	outstanding t	300-400	7
7	outstanding	400-1000	9.4

Table 3.3. show that, Eskişehir area has a small potential, hence the area is suitable for small scale wind power system.

3.4.3. Temperature

The temperature data is downloaded from NASA surface meteorology. Figure 3.6. shows rage of temperatures from 0.8^0C to 22^0C. the annual average temperature for Eskişehir area is 11.3^0C with July and August being the highest and January the lowest.

Figure 3.6. *Monthly average temperature, Eskişehir*

3.5. Components Considered For the Standalone and Grid Interactive Hybrid Energy System in HOMER Software

Figure 3.7. and 3.8. displays the components considered in HOMER software to find the best hybrid configuration for the study area. This way, the ideal combination to serve the department load can be obtained.

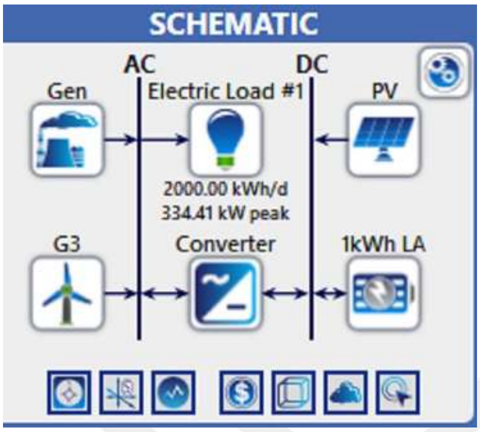


Figure 3.8. *HOMER diagram for a standalone hybrid energy system*

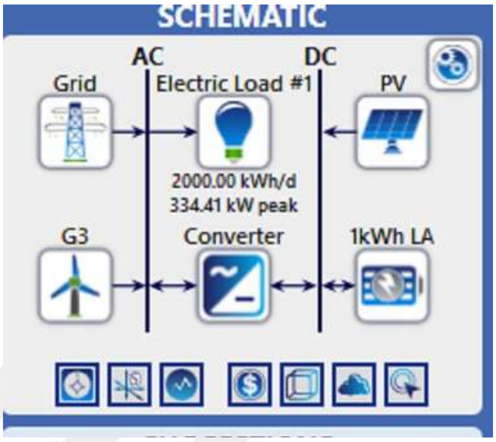


Figure 3.7. *HOMER diagram for grid interactive hybrid system*

3.6. Technical and Economic Characteristics of Components in Hybrid System

In Turkey, the cost of electricity from the grid is 0.18 $/kWh and the sell back price is 0.13 $kWh while diesel price is 1.13 $/L which is loaded into HOMER program. The software uses some input parameters such as hourly mean wind speed, solar radiation and load data. The technical characteristics and cost details of diesel generator, wind turbines, photovoltaic modules, batteries and the power converter are also added to the program. The program uses these inputs to achieve simulation, optimization and sensitivity investigation and come up with the most economical hybrid configuration according to their NPC and COE [4]. The five main components used as inputs to HOMER pro are: wind turbine, solar panel, generator, system converter, batteries and the grid. This section discusses these components and their technical and economic parameters.

3.6.1. PV panel

The PV panel used is generic plate PV manufactured by generic with rated capacity of 1 kW. The temperature of the panel is 47^{0}C and its efficiency is 13%. Its capital cost includes transport, mounting, wiring and installation of the system while the derating factor is made up of wire losses, shading from trees, dirt cover and aging [4]. The technical and economic characteristics of the PV panel are presented in Table 3.4 below.

Table 3.4. *Technical and economic characteristics of solar panel in HOMER program*

PV system	
Type of model	Generic flat plate PV
Peak power (kW)	1
Efficiency (%)	13
Capital cost ($)	2500
O&M cost ($)	50
Derating factor (%)	80
Life time (years)	25

3.6.2. Wind turbine

HOMER's generic 3 kW wind turbine with an elevation of 17 meters is used. The energy produced by the wind turbine depends on the availability and differences in the wind speed. Wind turbine naturally starts producing power when wind speed is between 2-4 m/s meaning the blades start to rotate and stops between the wind speed of 25-30 m/s known as cut-off speed [4]. Technical and economic characteristics of the wind turbine is presented in Table 3.5.

Table 3.5. *Technical and economic characteristics of the wind turbine*

Wind turbine	
Model type	Generic wind turbine
Maximum power (kW)	3
Capital ($/year)	18000
O&M cost ($/year)	180
Hub height (m)	17
Life time (years)	20

3.6.3. Battery bank

Battery is a vital portion of a hybrid energy system because it stores excess energy and provides power at night when renewables are not available. Therefore, keeping stability in the system. HOMER's generic 6 V lithium ion battery is used for the study. Technical and economic characteristics of the battery are given in Table 3.6 [4].

Table 3.6. *Characteristics of the battery*

Battery storage	
Voltage (V)	12
size (kWh)	1
Minimum State of Charge (%)	40
Capital ($)	300
Cost of replacement ($)	300
O&M cost ($/year)	10
Lifespan (years)	15

3.6.4. Diesel generator model

Hybrid energy system often requires a diesel genset for backup [26]. HOMER's generic diesel genset is utilized in the study. Diesel price of 1.13 $/L is applied by considering price of diesel in Turkey [4].. Technical and economic characteristics of the generator are given in Table 3.7.

Table 3.7. *Characteristics of diesel generator*

Generator	
Size	Auto-sizing
Capital ($)	500
Cost of Replacement ($)	500
O&M cost ($/hr)	0.03
Fuel Price ($/L)	1.13
Lifespan (operating hours)	15000
Lowest load ratio (%)	25

3.6.5. Converter model

System converter is needed for the hybrid renewable energy system to sustain the energy flow between AC and DC electrical machineries. It consists of an inverter and a rectifier to do the changes from DC to AC and vice versa. HOMER's generic system converter is used [4]. The technical and economic characteristics of the system converter are listed in Table 3.8.

Table 3.8. *Technical and economic specs of a converter in HOMER program*

Converter	
Size of converter (kW)	1
Capital ($)	300
Cost of replacement ($)	300
O&M cost ($/year)	0
Lifespan (years)	15
Efficiency (%)	95

3.6.6. Grid

The utility grid is adopted to send surplus power to the grid when the load demand is satisfied. but when there is shortage of renewable energy power, then power is bought from the grid. The price of the utility power considered is 0.18 $/kWh and the sell back price of 0.13 $/kWh.

3.7. Dispatch Strategy

Aside from selecting different components, HOMER makes numerous decisions concerning the working together of components and if the power be sent to the grid or purchased from it, whether batteries be charged or discharged and when the generator should operate. all these decisions take place for every hour of the day.

HOMER possesses two dispatch strategies, the load following strategy (LFS) and the cycle charging strategy (CCS). Load following strategy, is a dispatch strategy where diesel genset generates the required power when operating and the batteries are charged by the renewables. Hence it is suitable for systems with good renewable energy potential. Cycle charging strategy, is a dispatch strategy where diesel genset operates at maximum capacity and the surplus energy is used to charge the batteries. It is best suited for systems with bad renewable energy potential. This way, battery's charge-discharge cycle is reduced, increasing the battery life and reducing battery replacement cost.

Therefore, for the proposed hybrid energy system, LFS is adopted where the batteries will be charged by the renewables to minimize emissions and reduce fuel price [36, 38, 39].

3.8. Mathematical Model of PV Panel Power

The solar panel's energy production depends on the solar insulation falling on the surface of PV, the panel is given an angle to face the sun and also to give the panel good condition to cool in order to have higher energy production [40]. The solar panel's generation power can be computed using the equation below [41]:

$$\mathrm{P}_{pv} = \mathrm{Y}_{pv} \times \mathrm{f}_{pv} \frac{\mathrm{G}_t}{\mathrm{G}_{t,STC}} \tag{3.1}$$

where, Y_{pv} is the solar panel rated power under STC, f_{pv} is the derating factor of the panel consisting of factors such as soiling, losses in wires, shading on the panel, covering by the snow and the $\mathrm{G}_{t,STC}$ is the incident solar insulation at STC.

According to Akram, the PV panel output can be calculated from the equation given below [42]:

$$\mathrm{P}_{pv} = \mathrm{N} \times A_m \times \eta_g \times \mathrm{G}_t \tag{3.2}$$

Where P_{pv} is the PV output, N is the sum of solar panels used, $A_m$is the solar panel's area (m^2), $\eta_g$is the panel efficiency and G_t the global insulation falling on the panel (W/m^2)

When the PV model temperature is known, it is vital to consider the PV variation efficiency due to thermal impacts. Therefore, the PV panel generating power P_{PV} can be calculated as follows:

$$\mathrm{P}PV = \mathrm{Y}_{pv} \times \mathrm{f}_{pv} \left[1 + \alpha_P \left(\mathrm{T}_C - \mathrm{T}_{C,STC}\right)\right]\left(\frac{\mathrm{G}_t}{\mathrm{G}_{t,STC}}\right) \tag{3.3}$$

Where α_P is the panel's temperature coefficient ($\%/^0C$), T_C is the panel's instantaneous temperature and $\mathrm{T}_{C,STC}$ is the temperature of the PV panel (^0C) at STC. Properties of standard test conditions are solar radiation of 1 kW/m^2, temperature of PV cell of 25^{0}C and without wind [40].

The PV cell temperature T_C is equal to the outside temperature during the night, but at daytime the cell temperature of the PV exceeds the outside temperature by 30^{0}C or more. The temperature of the PV cell can be obtained by the equation below [43]:

$$Tc = T_a + T_{c,NOCT} - T_{a,NOCT}\left(\frac{G_t}{G_{t,STC}}\right)\left(1 - \frac{\eta_{mp}}{T_a}\right) \tag{3.4}$$

Where T_a represents the outside temperature (^{0}C), $T_{c,NOCT}$ is the nominal operating cell temperature at 20^{0}C, $\frac{G_t}{G_{t,STC}}$ is the solar irradiance at (0.8 kW/m^2), η_{mp} is efficiency of the panel (%),

3.9. Mathematical Modelling of Wind Turbine Power

As far as an object is under continuous acceleration a, its kinetic energy E having mass m and velocity v is equivalent to the work completed W in moving that object from its stationary position to a distance s using a force F, i.e. E = W= Fs. According to Newton's second law of motion.

$$F = ma \tag{3.5}$$

Hence the kinetic energy becomes

$$E = mas \tag{3.6}$$

Rearranging the formula $v^2 = u^2 + 2as$, it becomes a= $\frac{v^2-u^2}{2s}$ where u initial velocity of the object. Imagining the initial velocity to be zero, the equation becomes a= $\frac{v^2}{2s}$. Hence the final formula results to;

$$E = \frac{1}{2}mv^2 \tag{3.7}$$

This formula is true for solid with constant mass and since wind is air in motion, both density and velocity keep changing making the mass to change. But again, assuming that the density is constant and following the kinetic energy law above, the kinetic energy of air having mass m and in motion with a speed v_w can be determined using the equation below. The power in the wind is determined by the rate of variation of kinetic energy [44]:

$$P = \frac{dE}{dt} = \frac{1}{2}\frac{dm}{dt}v^2vw \tag{3.8}$$

The rate of mass flow $\frac{dm}{dt}$ is simplified to $\frac{dm}{dt} = \rho Avw$, where A is the area that the wind passes through and ρ is density of air [45, 46]. The power becomes:

$$P = \frac{1}{2}\rho Av^3w \tag{3.9}$$

But the actual power from wind turbine is the difference between the incoming and the outgoing wind powers [44], i.e.

$$Pw = \frac{1}{2}\rho Av_w (v^2_u - v^2_d) \tag{3.10}$$

Where v_u is the incoming wind speed into the rotor blades in m/s and v_d is the outgoing wind speed which coming out of the rotor blades in m/s. These two velocities make up the blade tip speed ratio. With the average of velocities entering and leaving the rotor blades [47], equation 3.8 becomes;

$$Pw = \frac{1}{2}\rho Av_u^3c_p \tag{3.11}$$

c_p is the fraction of wind coming and the one leaving the rotor blades and its often known as Betz limit also known as coefficient of power or rotor efficiency. Its value is not constant as it changes with ratio of tip speed of wind turbine [44].
λ characterise the tip speed ratio and is given as:

$$\lambda = \frac{v_d}{v_u} \tag{3.12}$$

$$\lambda = \frac{\text{blade tip speed}}{\text{wind speed}} \tag{3.13}$$

The blade tip speed can be determined from the turbine's rotation speed and the length of blade.

$$\text{blade tip speed} = \frac{\text{turbine's angular speed(w)} \times R}{\text{wind speed}} \tag{3.14}$$

Where R is the turbine radius and w which angular speed is calculated in rad/s.

$$C_P = \frac{(1+\lambda)(1-\lambda)}{2} \tag{3.15}$$

Finally, the value of C_p becomes 59.3%. this means that wind turbines can only convert 59.3% of the kinetic energy into mechanical energy. Although in real world the power coefficient is below the Betz limit with values between 35-45%. After considering several factors affecting the wind turbine such as the number of the blades and its shape, speed of rotor, gearbox and bearings used, only 10-30% of wind power is converted to practical power [44].

3.10. Modeling of Battery Bank

Battery bank in a hybrid renewable system is used for three different purposes; first one is for storing the energy that would be used if the renewables are not available due to climatic conditions.

Second, the battery provides power at night since the sun is no long available and lastly, to avoid the use of the backup Genset. Meaning, the battery acts as an energy source supplying power to the load. All this depends on the battery's state of charge (SOC), the battery's capacity and the rate it charges and discharges. The storage capacity of the battery is illustrated in equation [46].

$$\mathrm{C}wh = \frac{(\mathrm{E}L \times \mathrm{AD})}{(\eta \times \eta \times \mathrm{DOD})} \tag{3.16}$$

Where DOD is depth of discharge of the battery, η_{Batt} and η_{in} are the battery and inverter efficiency, AD is autonomy days, E_L daily energy load.

3.11. Technical and Economic Evaluation Criteria

Homer program uses technical and economic specifications and input parameters to come up with the optimal hybrid configuration. The optimal configuration is arranged according NPC and COE.

3.11.1. Net present cost (NPC)

The major technical and economic evaluation criterion of the HOMER program is NPC. Net Present Cost is defined as the cost of installing and operating hybrid system during its lifespan. It consists of all the profits and costs in a Project's lifespan, with cash flows of the future reduced to the present value. Hybrid system's economic output is studied for the purpose of finding the NPC [4, 5, 45]. The NPC is computed using the equation below.

$$\mathrm{NPC} = \frac{\mathrm{TAC}}{\mathrm{CRF}\ (\mathrm{i}, \mathrm{Rproj})} \tag{3.17}$$

Where, TAC is the total annualized cost ($); it is addition of the total annualized cost of each components of the hybrid energy system consisting of capital, replacement, O&M and price of fuel.

CRF is the capital recovery factor; which is a formula used to compute the present value of a sequences of identical yearly cash payments, i is the interest rate (%) and R_{proj} is lifespan of the project [5, 47, 48]. Formula for CRF is presented in the equation below:

$$\mathrm{CRF(i, N)} = \frac{\mathrm{i(1+i)^N}}{\mathrm{(i+1)^{N-1}}} \quad (3.18)$$

Where, i is the annual real interest rate and N is the sum of years

3.11.2. Annual real interest rate

Annual real interest (i) is an interest rate that has been modified to eliminate the impacts of inflation to reflect the real cost [4, 5, 39]. The formula for annual real interest rate is given as:

$$i = \frac{i^i - f}{1 + f} \quad (3.19)$$

Where, i is the real interest rate. i^i is the nominal interest rate. f is the inflation rate per year.

3.11.3. Levelized cost of energy (COE)

The cost of energy is the average cost per kWh of energy generated by hybrid renewable energy system. It is also a ratio of the annualized system cost by the total electricity generated [4, 5, 49]. The COE for hybrid energy system is calculated as follows:

$$\mathrm{COE} = \frac{\mathrm{TAC}}{\mathrm{E}_{ac}} \quad (3.20)$$

Where E_{ac} is the total electrical energy produced?

3.11.4. Resale value

It is the sale value of a component at the end of its lifespan and is calculated as [41, 50, 51].

$$\mathrm{SC} = \frac{\mathrm{C_{RC}} \times \mathrm{T}_{rem}}{\mathrm{T}_{com}} \quad (3.21)$$

C_{RC} is the cost of replacement ($), T_{rem} is the remaining life and T_{com} is the lifespan of system's component.

3.11.5. Sensitivity inputs

The input variables for the hybrid renewable energy system are often uncertain and keeps changing. This becomes a problem in designing the hybrid system. Hence, HOMER program comes to play to solve the problem: The software performs sensitivity investigation each hour, this way doubts in the load profile can be considered.

Therefore, the sensitivity investigation permits the system designer to make a good and practical design despite doubts in the main variables. The hourly data used for the sensitivity investigation consist of 2560 values each. Sensitivity analysis helps the HOMER program produce the optimal hybrid configuration as regards to NPC and COE as well as environmental pollution [34, 35].

4. RESULTS AND DISCUSSION

The simulation results and discussion from HOMER software are presented. HOMER performs simulations, optimization and sensitivity investigation to come up with the most cost-effective hybrid configuration in terms of technical and economic cost. The optimization results of both the standalone and the grid connected hybrid energy system are analysed and compared. HOMER ranks the optimal system according to their NPC and COE in ascending order, the most economical system is showed at the top and its able to supply the load at the lowest NPC.

4.1. Optimization Results for a Standalone Hybrid Energy System

Table 4.1. shows the optimization results of a standalone hybrid renewable energy system which contains optimal configuration, dispatch strategy (DS), NPC, COE and RF. The optimal system is capable to supply the load demand to the study location in Eskişehir Technical University.

Table 4.1. *Optimization results for different standalone HES configuration*

PV (kW)	WT (kW)	DG (kW)	Battery (no)	DS	NPC ($)	COE ($/kWh)	RF (%)
607	**0**	**370**	**1,613**	**LFS**	**4.29 M**	**0.455**	**81.1**
593	1	370	1,581	LFS	4.31 M	0.457	80.4
0	0	370	0	LFS	7.22 M	0.765	0
1,417	10	0	7,189	LFS	8.83 M	0.936	100

As can be seen from Figure 4.1, PV/DG/Battery is the most economical system with 607 kW solar panel, one 370 kW diesel genset and 1,613 strings of batteries. The system NPC of $4.29 M and it can provide power at cost of $0.455/kWh to meet load demand of a department in Eskişehir Technical University. The system uses a load following dispatch strategy to reduce the usage of diesel generator and it has a high renewable fraction of 81.1% making it to consumes less diesel (42258L per year) hence reducing environmental pollution.

Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Sensitivity		Architecture						Cost				System	
Diesel Fuel Price ($/L)	Solar Scaled Average (kWh/m²/day)	PV (kW)	G3	Gen (kW)	1kWh LA	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
1.13	3.00	750		370	1,527	294	LF	$5.03M	$0.533	$187,709	$2.61M	72.8	60,955
1.13	4.26	607		370	1,613	285	LF	$4.29M	$0.455	$156,252	$2.27M	81.1	42,258
1.13	5.00	515		370	1,668	294	LF	$4.02M	$0.426	$151,426	$2.06M	82.5	39,144
1.13	6.00	492		370	1,540	300	LF	$3.78M	$0.401	$140,464	$1.97M	85.0	33,487
1.50	3.00	815		370	1,557	298	LF	$5.30M	$0.562	$195,019	$2.78M	76.0	53,659

Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

Architecture						Cost				System		Gen		
PV (kW)	G3	Gen (kW)	1kWh LA	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)
607		370	1,613	285	LF	$4.29M	$0.455	$156,252	$2.27M	81.1	42,258	1,359	137,910	42,258
593	1	370	1,581	304	LF	$4.31M	$0.457	$159,477	$2.25M	80.4	43,799	1,409	142,927	43,799
		370	295	65.4	LF	$5.63M	$0.597	$412,768	$293,309	0	221,120	5,865	759,375	221,120
	1	370	288	68.7	LF	$5.65M	$0.599	$413,244	$310,197	0	220,922	5,867	758,477	220,922
82.9		370		60.9	LF	$7.17M	$0.760	$522,886	$410,608	0	284,852	8,760	941,758	284,852
83.5	1	370		58.3	LF	$7.19M	$0.762	$522,995	$429,403	0	284,630	8,760	940,817	284,630
		370			LF	$7.22M	$0.765	$544,344	$185,200	0	305,006	8,760	1,027,162	305,006
	1	370			LF	$7.24M	$0.767	$544,429	$203,200	0	304,750	8,760	1,026,080	304,750
1,417	10		7,189	346	LF	$8.83M	$0.936	$219,966	$5.98M	100	0			

Figure 4.1. *HOMER optimization results for standalone hybrid energy system*

The next economical hybrid is PV/WT/DG/battery system with 593 kW PV panel, 3 kW wind turbine, 1581 batteries and 370 kW diesel genset and NPC of $4.31M and COE of 0.457$/kWh. It has low renewable fraction of 80.4% when compared to the first hybrid system hence it releases more CO_2 emissions because the generator operates more hours and consumes more diesel (43,799 L). Due to the generator operating more hours, there is excess electricity of 16.3%.

The third economical hybrid configuration is the diesel genset/battery system which supplies power at a COE of 0.597$/kWh with 0% renewable fraction while the hybrid configuration with 100% renewable energy supplies power at a COE of 0.936$/kWh. Therefore, the diesel genset/battery configuration is more economical than the system with the 100% renewable energy and but not environmentally friendly.

The PV/DG/Battery hybrid arrangement is not only the most economical but releases less pollution when compared to the diesel only system (110.6 and 798.4 tonnes of CO_2). Therefore, it is cost-effective system from reliability, economic and environmental standpoint. From the simulation we see that, the diesel only system is neither economical nor environmentally friendly to meet the load demand.

The generator accounts for only 5% of the system's capital cost, while the solar panel is responsible for 60% of the initial investment. But after installation, it is inexpensive to maintain and operate the solar panel compared to diesel genset. So, in the end the diesel genset is accountable for 59.5% of yearly cost of the system.

Figure 4.2. below displays the PV/DG/battery hybrid system's cost summary of each components based on NPC.

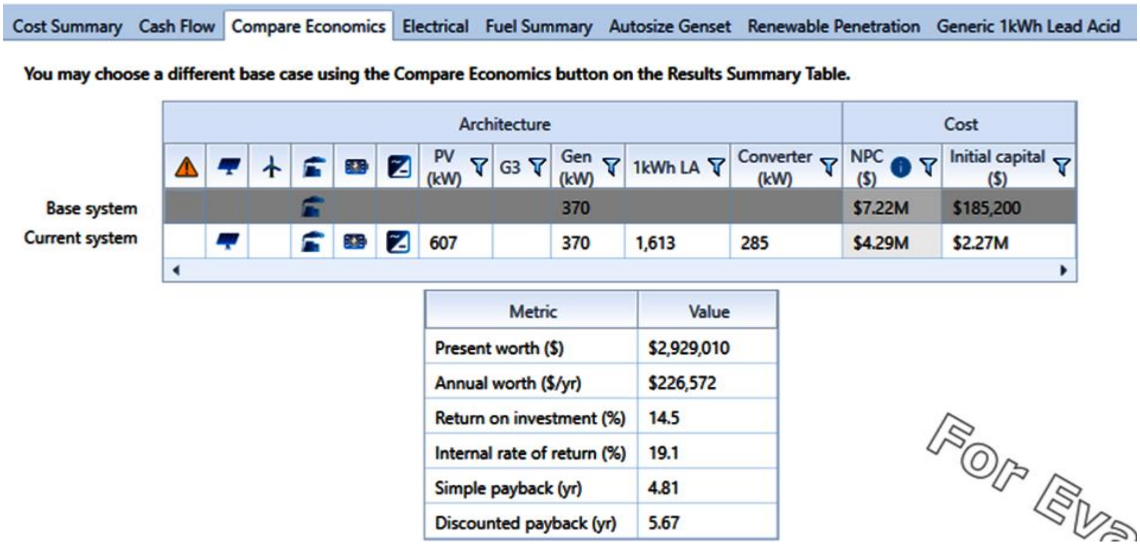
Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	$185,000.00	$150,825.00	$195,010.29	$617,310.32	($32,573.88)	$1,115,571.73
Generic 1kWh Lead Acid	$483,900.00	$875,177.63	$208,520.84	$0.00	($102,407.49)	$1,465,190.99
Generic flat plate PV	$1,518,534.52	$0.00	$78,523.52	$0.00	$0.00	$1,597,058.04
HOMER Load Following	$200.00	$0.00	$64.64	$0.00	$0.00	$264.64
System Converter	$85,631.92	$36,331.38	$0.00	$0.00	($6,837.93)	$115,125.37
System	$2,273,266.44	$1,062,334.01	$482,119.29	$617,310.32	($141,819.30)	$4,293,210.76

Figure 4.2. *Cost summary of the PV/DG/battery configuration*

Figure 4.3. shows cost distribution among the components of the PV/DG/battery hybrid configuration. Cash flow of the system in terms of capital, replacement, O&M and salvage cost are displayed below.

Figure 4.3. *Cash flow summary of the PV/DG/battery hybrid energy system by cost type*

HOMER program calculates the ROI, IRR and payback time of the PV/DG/Battery hybrid renewable energy system. The system pays for itself after 5 years as shown in Figure 4.4.



Cost Summary | Cash Flow | Compare Economics | Electrical | Fuel Summary | Autosize Genset | Renewable Penetration | Generic 1kWh Lead Acid

You may choose a different base case using the Compare Economics button on the Results Summary Table.

	Architecture											Cost	
							PV (kW)	G3	Gen (kW)	1kWh LA	Converter (kW)	NPC ($)	Initial capital ($)
Base system									370			$7.22M	$185,200
Current system							607		370	1,613	285	$4.29M	$2.27M

Metric	Value
Present worth ($)	$2,929,010
Annual worth ($/yr)	$226,572
Return on investment (%)	14.5
Internal rate of return (%)	19.1
Simple payback (yr)	4.81
Discounted payback (yr)	5.67

Figure 4.4. *Comparing economics*

4.1.1. Energy production

The PV/DG/battery hybrid configuration's monthly energy production from different components is presented in Figure 4.5. The total annual electricity production is 987.660 MWh. The PV panel and the generator produces 86% and 14% of electrical energy annually. The system has a renewable fraction of 81.1% and excess electricity of 18%. The generator used load following strategy hence it only generates the needed power for the load in case the renewables are not available.

Figure 4.5. *The PV/DG/battery hybrid system's energy production*

4.1.2. Greenhouse gas emissions

The PV/DG/battery hybrid energy system's greenhouse gases emissions are presented in Figure 4.6. The system emits 110.6 tons of CO_2 per year while the diesel only system emits 798 tons of CO_2 per year, this means 687.4 tons of CO_2 is avoided. Almost 86% of CO_2 emission reduction.

y Autosize Genset Renewable Penetration Generic 1kWh Lead Acid Generic flat plate PV System Converter Emissions

Quantity	Value	Units
Carbon Dioxide	110,615	kg/yr
Carbon Monoxide	697	kg/yr
Unburned Hydrocarbons	30.4	kg/yr
Particulate Matter	4.23	kg/yr
Sulfur Dioxide	271	kg/yr
Nitrogen Oxides	655	kg/yr

Figure 4.6. *Greenhouse gas emissions*

4.2. Sensitivity Analysis

HOMER program uses algorithm to find the optimal hybrid configuration based on inputs by user. Some of this input may have uncertainties especially solar irradiance, wind speed and values of diesel price. So, simulations are done to determine these uncertainties and how it affects the NPC and COE. Sensitivity investigation removes all infeasible configurations and ranks the viable system according to their NPC and COE to supply the load demand. The values considered for the diesel price are \$0.3, \$0.4, \$0.5, \$1.13 and \$1.5 and for solar irradiance is 3.0 ,4.26, 5.0 and 6.0 kWh/m^2/day with a wind speed of 4.76 m/s.

4.2.1. Global solar insulation and diesel price

The solar panel's energy production depends on the intensity of solar radiation. Figure 4.7. shows sensitivity analysis for various solar insulations and price of diesel with a wind speed of 4.76 m/s.

Figure 4.7. illustrates that the PV/DG/battery hybrid configuration is the most favourable system type for most parts of sensitivity variables studies such as solar irradiance and diesel price except the blue area. Because of this, PV/DG/battery hybrid system is the most economical configuration. The DG/battery becomes optimal system type for diesel price less as the solar insulation rises, the COE declines. This is due to rise in the renewable percentage, since more energy comes from the renewables, the diesel genset provides less power hence less fuel usage leading to less COE.