TECHNO-ECONOMIC OPTIMIZATION OF PV-WIND-BATTERY HYBRID SYSTEMS

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ABSTRACT

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In this study, the technoeconomic optimization of hybrid renewable energy systems were investigated for a small community with 50 households located in Izmir Institute of Technology (IZTECH) Campus, Izmir. The renewable-based power systems have received significant attentions recently due to the recent effort for the transition from fossil fuels to renewable energy, but their technical and economical feasibilities for different sectors and application areas and the related optimum system configurations haven't been clearly addressed. To fill this research gap, PV-battery and wind turbine-battery system were analyzed for a small community from technical and economic point of views and the most economic configurations were explored for different level of grid-dependency by using the Loss of Power Supply Probability (LPSP) method. The annual electricity load profile was built in hourly basis based on the monthly total electricity consumption of each house and electricity consumption habits of residents. PV and wind turbine power outputs, the involvement of batteries were modelled in MATLAB/Simulink considering the meteorological data (IZTECH Meteorological Mast and NASA POWER), types of PV panel, wind turbine and battery. The mismatch between energy demand and supply was determined and different hybrid configurations were considered to cover this mismatch to different extents. The optimum number of PV panel, wind turbine and batteries were determined and the levelized cost of electricity were calculated for each scenario. The most economic configuration is the one consisting of 3 wind turbines and 7 batteries with 49.62% energy utilization from the grid.

ÖZET

PV-RÜZGAR-BATARYA HİBRİT SİSTEMLERİNİN TEKNO EKONOMİK OPTİMİZASYONU

Bu çalışmada, İzmir Yüksek Teknoloji Enstitüsü (İYTE) Yerleşkesinde yer alan 50 hanelik küçük bir topluluk için hibrit yenilenebilir enerji sistemlerinin teknoekonomik optimizasyonu incelenmiştir. Yenilenebilir enerjiye dayalı enerji sistemleri, son yıllarda fosil yakıtlardan yenilenebilir enerjiye geçiş çabaları nedeniyle büyük ilgi görmektedir, ancak farklı sektörler ve uygulama alanları için teknik ve ekonomik fizibiliteleri ve ilgili optimum sistem konfigürasyonları net bir şekilde ele alınmamıştır. Bu araştırma boşluğunu doldurmak için, küçük bir topluluk için PV-batarya ve rüzgar türbini-batarya sistemi teknik ve ekonomik açıdan analiz edildi ve Güç Kaynağı Kaybı Olasılığı kullanılarak farklı şebeke bağımlılığı seviyeleri için en ekonomik konfigürasyonlar araştırıldı. (LPSP) yöntemi. Yıllık elektrik yükü profili, her evin aylık toplam elektrik tüketimi ve konut sakinlerinin elektrik tüketim alışkanlıkları baz alınarak saatlik bazda oluşturulmuştur. PV ve rüzgar türbini güç çıkışları, bataryaların katılımı, meteorolojik veriler (İZTECH Meteorolojik Direk ve NASA POWER), PV panel tipleri, rüzgar türbini ve batarya dikkate alınarak MATLAB/Simulink'te modellenmiştir. Enerji talebi ve arzı arasındaki uyumsuzluk belirlendi ve bu uyumsuzluğu farklı boyutlarda karşılamak için farklı hibrit konfigürasyonlar düşünüldü. Optimum PV paneli, rüzgar türbini ve pil sayısı belirlenmiş ve her senaryo için seviyelendirilmiş elektrik maliyeti hesaplanmıştır. En ekonomik konfigürasyon, şebekeden %49,62 enerji kullanımı ile 3 rüzgar türbini ve 7 bataryadan oluşan konfigürasyondur.

Dedicated to my grandmother

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CHAPTER 1

INTRODUCTION

1.1. Importance of Renewable Energy

As population density and energy consumption per capita increases, the overall energy consumption increases accordingly. This increase has caused environmental pollution and climate change due to fossil fuel domination in energy generation. The dramatic increase in consumption and the concern about the availability and environmental impact of fossil fuels have promoted the search for new energy alternatives. Renewable energy seems to be the best alternative due to its sustainable nature and local availability. Therefore, countries have developed new energy policies to accelerate the transition from fossil fuels to renewable energy sources. The current available renewable energy sources are wind energy, solar energy, hydropower, biomass energy, and geothermal energy, wave, and tidal energy (Pani et al., 2022).

1.2. Renewable Energy Status in the World

The urgent need for decarbonization and local energy sources have increased the importance of renewable energy utilization, but the share of renewable energy in total energy generation is still less than 50% A few developed and developing countries consider renewable energy investment seriously such as European Union countries, UK, China, Japan and USA. These countries have increased the renewable capacity dramatically thanks to huge incentives provided by governments. For other countries, the change in renewable energy capacity is relatively small due to the cost of this transition. Even if there has been a dramatic improvement in the cost of renewable energy technologies for the last decades, the related economy and the system efficiency needs further improvement for large-scale implementation. Therefore, many research studies has focused on the cost reduction, efficiency improvement and technoeconomic feasibilities of renewable energy implementation.

The total renewable-sourced energy power capacity has increased significantly, and China is the leading country in this effort. The total renewable energy electricity generation in the top 10 countries in 2020 is 2.183.034,4 GWh and the shares of renewable energy sources in total energy electricity generation are as follows: Solar 12,62%, wind 24,62%, biomass 8% and the others 54,75%. The International Energy Agency amended the Renewable Energy Law in 2009 due to the increase in carbon pollution and the increasing energy demand because of population density (Balakrishnan et al., 2020). As seen Figure 1.1 below, the top 10 countries renewable energy electricity generation, 2020 ("IRENA and International Energy Agency").

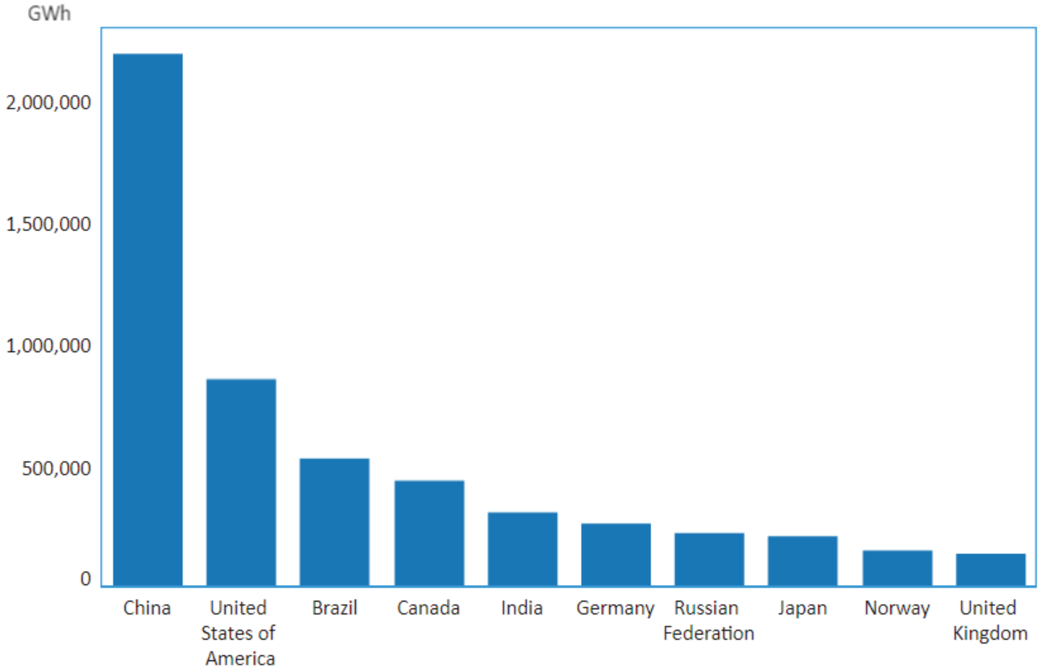


Figure 1.1 The top 10 countries renewable energy electricity generation, 2020 (Source: URL1 https://www.irena.org/Data, 2022).

1.3. Renewable Energy Status in Turkey

Since Turkey is a developing country, energy consumption has been increasing in recent years. For instance, the International Energy Agency (IEA) (2018) stated that Turkey's energy consumption increased by approximately 48% from 2000 to 2014. However, energy production remained low compared to energy consumption. According to the results of the research, Turkey's foreign dependency on energy has increased by 70% since 2000. For this reason, the provision of energy resources and the creation of investments have become Turkey's goal. As a result, the participation of private institutions was ensured with the liberalization of the energy market. In this way, energy production increased by 43% from 2002 to 2017. At this time, Energy Exchange

Istanbul was established in 2015. Thus, Turkey is following an innovative path in renewable energy which will play an important role in the future (Bulut & Muratoglu, 2018). As an example, you may see renewable energy capacity in 2021 for Turkey in Figure 1.2 below (URL1 https://www.irena.org/Data, 2022).

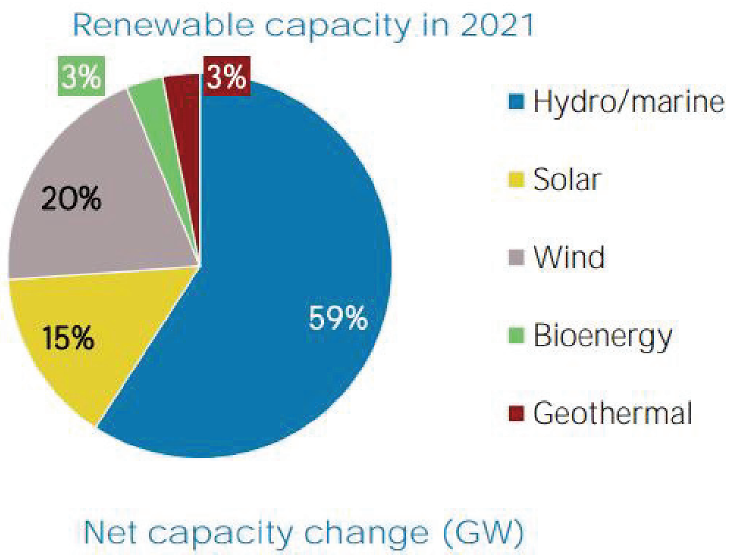


Figure 1.2 Renewable energy capacity,2021 in Turkey (Source: URL1 https://www.irena.org/Data, 2022

1.4. Renewable Energy Integration to Households

The increase in the World population and accordingly the rapid heighten in energy consumption has increased the importance of energy need. At the same time, reducing environmental pollution and carbon emission have carried scientist along to new path. With the integration of renewable energy into electricity generation, it is aimed to reduce environmental pollution and at the same time to promote sustainability. In this way, the concept of micro grid emerged. In recent years, batteries that store energy with energy sources such as wind and solar have come to an important point in the use of micro grid. Besides, the micro grid can be operated either grid connected or off-grid. Thus, the integration of renewable energy has recently increased in popularity due to its economic and environmental benefits. In addition, modelling the micro grid with demand side management play a significant role in preventing energy inefficiency and reducing costs (Sarker et al., 2020).

1.5. Objectives of Thesis and Outline

The main objective of the thesis is to evaluate technoeconomic optimization of hybrid renewable energy systems designed for a small community with 50 households located in Izmir Institute of Technology (IZTECH) campus, Urla, Izmir. The hybrid renewable energy system consists of solar panel and wind turbine(s) as power sources and Li-ion batteries for energy storage. The specific objectives are:

i) To determine the annual load profile of households

ii) To determine the annual solar and wind energy potential of the related location

iii) To determine the optimum system configuration for different level of grid dependency.

iv) To find out the most economical solution for meeting the total electricity of need.

To achieve the objectives, the related literature on technoeconomic optimization of renewable energy system was first analyzed (Chapter 2), which helped to evaluate and choose the tools, methods, and methodology. Then the electricity load and meteorological data related to solar and wind energy were described (Chapter 3) and the main approaches to determine the annual electricity load, solar and wind energy power output and the optimization method used were explained (Chapter 4). The technoeconomic optimization was applied to two different scenarios: (i) PV+battery and (ii) Wind+battery. The optimum number of PV panels, batteries and wind turbine were determined by Loss of Power Supply Probability (LPSP) method and the most economic configuration was evaluated by simple payback time and levelized cost of eletricity (Chapter 5). The main conclusions were presented at the end of thesis.

CHAPTER 2

LITERATURE SURVEY

2.1. Technoeconomic Analysis of Renewable Energy System for Household

The related literature on technoeconomic analysis of hybrid renewable energy systems was investigated and summarized in the following parts. Duman & Güler, (2018) investigates meeting electrical energy demand of a hypothetical off-grid settlement consisting of 12 detached houses, a small market and 20 streetlights by HOMER software. Photovoltaic panels (PV), wind turbines, fuel cells (FC), and diesel generators were considered for energy generation, while the battery, electrolyzer, and hydrogen tanks were included for energy storage. The analysis was made for the location of Çeşme, Izmir in Turkey, under two different occupancy scenarios (e.g., regular, and seasonal). Battery and hydrogen storage options were also compared, and the economic competitiveness of the two technologies was investigated for the related location. The results show that the Levelized cost of electricity (LCOE) of an off-grid system is higher than the cost of grid electricity, and the energy storage by batteries is economically more feasible than the storage via electrolyzer and hydrogen tanks.

In the other study, Dursun et al. (2012) performed an economic analysis of the combined wind and battery system for meeting the energy demand of a house in Gebze, Turkey. The number of required batteries for wind turbines with different capacities was determined to operate the system in an off-grid mode based on the maximum cumulative energy deficiency, and the system economy was analyzed. The hourly wind speed and the power curve of wind turbines were used to determine the power output. The most economical wind turbine capacity for the specified load profile was 2.5kW, and the optimum battery number for the related turbine was 44. The authors determined that LCOE and the total system cost were 0.82 $/kWh and $17,438.

Rezk & Dousoky, (2016) studied technical and economic analysis of standalone hybrid renewable energy systems for remote areas in Minya, Egypt, using HOMER software. Authors investigated six different configurations: (i)PV-battery, (ii) PV-fuel cell, (iii) Wind turbine-battery, (iv) PV-wind turbine, (v) wind turbine-fuel cell and (vi) PV-fuel cell-battery. The economic performance of these configurations was evaluated based on net present value (NPV) and cost of electricity (COE). The results show that the PV-fuel cell system has the lowest NPV, and COE values compared to other alternatives. Authors also considered the grid involvement and found that the grid extension is not economically viable for the considered configurations except for the wind turbine-battery system.

Hemmati, (2017) shows home energy management system (HEMS), including small scale wind turbine, battery energy storage system (BESS), load reduction option and fuel cell vehicle. The introduced HEMS not only determines the optimal charge-discharge pattern for BESS, but also determines the optimal capacity and optimal rated power of the BESS.

In this project, the consumption of all household appliances for a family of two in Çankırı, Turkey was determined by Issi & Kaplan, (2018). The load profile created for each household appliances in detail. While creating these load profiles, the models and power consumptions of the household appliances were learnt, and a measuring instrument was installed to each household appliance to measure their consumption and monitored. In the obtained results, it is significant to determine the load profiles of household appliances for home energy management. The results of this project can reveal the supply and demand of a family of two.

In the other study, Pipattanasomporn et al., (2014) determined the load profiles of similar major household appliances such as two washing machines, two air conditioner and an electric oven in Virginia and Maryland. At the same time, the demand response potentials of these household appliances were investigated. Thus, a device level dataset lies for use by university and industry research to advance more realistic load models, to analyze the demand response algorithm for home energy management, and thereby for energy management purposes.

In this research Borowy & Salameh, (1996), developed a methodology for optimal results of the number of batteries and PV array for a hybrid Wind/PV system. To obtain these results, wind speed and radiation data, which were monitored and found for 30 years, were used. The average output power of wind turbine and PV module was calculated for each hour of the day with these data. The load of a house in

Massachusetts was used for the load demand of the hybrid system. Thus, the optimum number of batteries and PV modules was found based on the minimum cost of the installed system for a given load and desired power.

Das et al., (2017) compared a hybrid PV-battery- Fuel Cell system with conventional diesel system as economic feasibility. This study investigated in 50 families in Sarawak, Malaysia. The economic analysis consists of net present cost (NPC) and cost of energy (COE). PV-battery system is the best choice as economic and environmentally friendly in the results of analysis.

Gan et al., (2015) studied the sizing model of components for different sites of a hybrid system which consists of wind turbines, photovoltaic panels, diesel generator, and battery storage. The authors focused on investigating the proper size of the batteries and the diesel generator usage in this study. The simulation of the model was analyzed at Matlab software. The future work of this project, complex modelling and testing of hardware are required to make predictions more precise. At the same time, obtaining historical data allows the load increase forecast to be considered.

In the other study was built to integrated techno-economic and renewable energy feasibility analysis using grid-connected and islanded mode to meet load demands. Ahmad & Zhang, (2021) performed three main analytical tasks which include optimization, simulation, and sensitivity analysis. The authors selected four sensitivity cases, including combinations of renewable energy sources such as wind turbine, photovoltaic, power grids, battery banks, converters, and diesel generator etc. In this article, capital costs, replacement costs, operating and maintenance costs, salvage costs, fuel costs, real time commercial load, and climate data were analyzed for techno-economic feasibility analysis. The results show that the grid-connected mode costs are two times lower than the islanded mode. Therefore, sensitivity case-2 was chosen to meet the load demand.

In this article, Aziz et al., (2019) supplied electricity to Iraq rural village to analyze techno-economic and environmental of different hybrid systems. To optimize these systems, the HOMER software was utilized using multi-year module. The aim of this study is to fill a research gap as optimal design with an off-grid PV/hydro/diesel/battery hybrid system. The authors proposed and evaluated five design cases that include PV, hydro, diesel generator, and battery energy storage. As a result of these cases, the best optimal solution was showed according to NPC results.

The aim of Rezzouk & Mellit, (2015) was to analyze techno-economic and feasibility of hybrid system that includes PV, diesel-battery, and battery were in the north of Algeria. These analyses were made according to many scenarios and were made an analyze according to determinant criteria that is about net present cost, load satisfaction, the cost of energy, energy excess, fuel consumption savings, operation costs of diesel generators and maintenance, CO2, and pollutants saving rates. As a result of these scenario, 25% PV-diesel-battery HES is the optimal configuration.

Zhang et al., (2021) worked on an optimal configuration of hybrid systems that consist of wind turbine and a photovoltaic system to supply with desired electricity power of workshop in an industrial area in Ardabil, Iran. The aim of the authors is to present techno-economic analyses to obtain the optimal cost using historic data from supply and demand sides. For analyses, 8 different cases were obtained such as Diesel, Diesel/Battery, PV/Diesel /Battery, Wind/Diesel/Battery, PV/Wind/Diesel/Battery, PV/Diesel, Wind/Diesel, and PV/Wind/ Diesel. As a result, most of generated energy was supplied from wind energy due to climate conditions of selected region.

Today, it is an extra cost to install a power line to supply the electricity needs in rural areas. Therefore, in this study, Iskanderani et al., (2020) considered a renewable energy system for rural area in Bangladesh. In this study, 4 types of demand scenarios were created by looking at the income level of those living in rural areas. HOMER software was used to find the most optimal techno-economic scenarios out of these scenarios. According to the results, it was determined that PV/diesel generator/battery power is the most economically beneficial method.

Electricity production from renewable energy sources affected El-houari et al., (2021) due to the depletion of fossil fuels. The aim of the authors was to make an analysis the economic, energy, and environmental for hybrid system that consist of wind, solar photovoltaic systems. Therefore, in this study, HOMER Pro software was used for economic evaluations. 24 cities that had different climate conditions were selected for these evaluations. According to the results, Eddakhla city was evaluated as the lowest levelized cost of energy.

The aim of Kumar & Tewary, (2021) in this study, is to find the best configuration of the best urban residential stand-alone hybrid energy systems that are technically and economically feasible and reliable. The simulations of these configurations were performed in the HOMER software. According to the simulation results, it showed that the average energy requirements can be met by PV, wind turbine, power generator(diesel), and battery backup system. This system was observed having more performance and more economic advantages compared to the others in terms of techno-economics.

In the other article, residents of Kalasatama region in Helsinki, Finland stated that they want to be self-sufficient in the field of energy. Therefore, Laitinen et al., (2021) started technical and economic studies in this filed. Hence, the aim of researchers is to find cost and technical optimal solutions for self-sufficiency rate. The components used in this project were wind turbine, PV panel, battery, and heat pump. To find the optimal solutions, two methods were implemented. The results show that for full energy, very high investments in renewable energy systems are required.

In this study, grid-connected renewable energy systems were used to satisfy growing demand. Besides, intermittent structure of renewable energy systems prevents their performance. Therefore, renewable energy systems were integrated with battery storage technology because of this challenge. Kebede et al., (2021) realized the Li-ion and Lead-acid batteries techno-economic analysis. For this analysis, they used the HOMER software. As a result, Li-ion batteries were found to be more suitable techno-economically than Lead-acid batteries.

In this study, solar panel, wind turbine, battery, and hydrogen were used in the microgrid system. The reason for the use of hydrogen is that hydrogen is of great interest in energy storage today. Tiong et al., (2022) reviewed 4 different scenarios for a 25-year project to select the best system to handle the electrical load. HOMER Pro software was used to analyze the system economic cost of suggested scenarios and to design the energy generation system. In the result of HOMER Pro simulations, the micro grid was the best techno-economically that was integrated with battery and hydrogen.

Sawle et al. (2018) performed a technical, economic, and environmental analysis of the hybrid PV-wind turbine-biomass gasifier-battery-diesel generator system for meeting the energy demand of a household located in Barwani, India, by using HOMER software and particle swarm optimization (PSO). The authors evaluated the performance of different combinations of hybrid systems based on LCOE and the amount of emission (e.g., CO2, CO, NO2, SO2, particulate matter, unburned hydrocarbon) produced annually. They found that the system with all components (PV-wind turbines-gasifier-battery-diesel generator) is the best choice, with an LCOE of 0.2899 $/kWh and a total emission of 12,346 kg/year. Agyekum et al. (2020) made a similar analysis for a district located in Mankwadze, Ghana. They compared two different hybrid systems in terms of their LCOE and NPV, namely (i) PV-wind turbine-diesel generator battery and (ii) Wind turbine-diesel generator- battery. They found that the system with PV is more feasible (0.382 $/kWh, $8,649,504) than the one without PV (0.396 $/kWh, $8,966,700).

Unlike the other studies, Laitinen et al. (2021) studied the techno-economic feasibility of renewable energy systems containing PV, wind turbines, batteries, heat storage, and heat pump for the Kalasatama district in Helsinki, Finland. Authors determined that a standalone system requires a high investment, and the system's life cycle cost can be significantly decreased (66%) by reducing the self-sufficiency rate to 76%. They also found that the investment in wind power is more reasonable than PV due to the higher utilization rate of wind power, and the battery significantly contributes to the system's total cost. AP-GR-02 07/04/2020

The techno-economic analysis of different battery technologies integrated with renewable energy systems was also studied in the literature. Kebede et al. (2021) analyzed the economic performance of Li-ion and lead-acid batteries integrated with grid-connected PV systems by HOMER software. The rate of charge and discharge cycling effect was also considered in this study. They found that the system with a Li-ion battery is economically more feasible than the system with a lead-acid battery with lower LCOE (0.32 €/kWh vs. 0.34 €/kWh) and NPV (€ 14,399 vs. € 15,106).

Different from the others, Tiong et al. (2022) investigated the techno-economic analysis of a PV-wind turbine-battery system with and without hydrogen storage unit in on- and off-grid mode for the Long Lama town in Malaysia. The authors found that the most cost-effective approach is the grid-connected PV-wind turbine battery with the hydrogen storage unit.

Literature studies show that the techno-economic analysis of hybrid renewable energy systems containing PV and wind turbines with battery storage was extensively studied. However, studies concerning the techno-economic optimization of renewable energy systems by Loss of Power Supply Probability (LPSP) method are scarce. In this study, we aim to investigate the techno-economic feasibility of a PV-wind hybrid system with batteries and determine the optimum capacity and configuration of the system by combining the LPSP method with basic economic analysis.

CHAPTER 3

SYSTEM DESCRIPTION

3.1. Description of Load and Meteorological Data

In this study, it was aimed to establish a hybrid system based on the load profiles of the lodgings of Izmir Institute of Technology, and a techno-economic optimization study of this system was carried out. This hybrid system is designed to be a wind turbine, solar panels, and a battery. Since the system is close to the lodgings, it was thought that it would be established in an area affiliated to Izmir Institute of Technology. The determined area is shown in Figure 3.1 and its coordinates are also shown. It is considered that there are 50 households in the lodging, and it is assumed that there are 3 people living in each household on average. Accordingly, a wind turbine, a solar panel and a battery were selected by looking at the load profiles of these households.

Firstly, a single wind turbine was assumed, and techno-economic optimization study was carried out by playing with the number of solar panels and batteries. Secondly, a separate techno-economic study was carried out by changing the number of wind turbines. Figure 3.2 shows the configuration of a residential with a hybrid system as an example. Thirdly, an on-grid study was carried out next to the hybrid system. The aim here is to show how the energy taken from the grid in 1% increments varies in terms of techno-economic compared to other studies. Figure 3.3 below shows the modeling made with Matlab/Simulink for this study. This modelling was made with reference to Tous & Hafith, 2014 and the arrangement was made according to the weather conditions of the region.

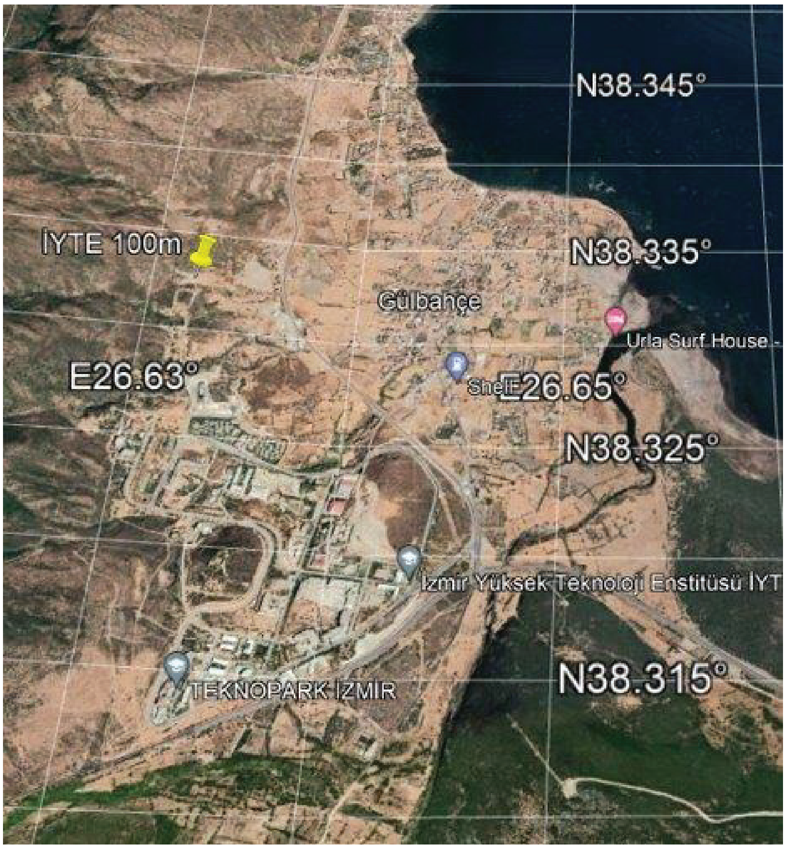


Figure 3.1 Location of hybrid system

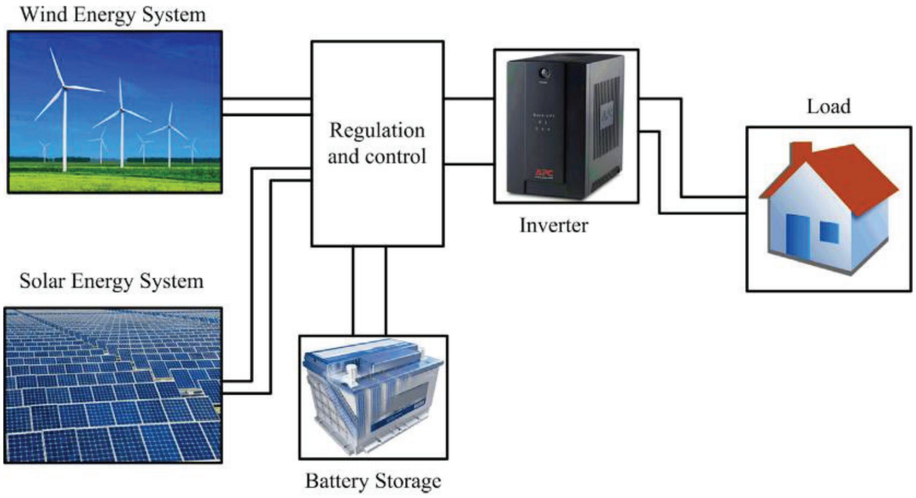


Figure 3.2 PV/Wind hybrid system representation (Source: Mahesh & Sandhu, 2015).

The modelling was first designed as a wind turbine, a solar panel and a battery, and energy productions were determined accordingly. PV-array and battery modules from Simulink were used in the modelling and their properties were defined separately. For the wind turbine and the load, real data were used and added to the system separately by looking at their power. Each component will be discussed in detail in the next steps.

3.2. Load Description

Knowing of forecasting electricity demands for households is important for both consumers and utilities. Utilities have little knowledge of consumers outside of all building load levels(Barbour & González, 2018).

Home energy management algorithm are important for responding to electricity demands in residences. In some sources, it is assumed that household appliances work steadily at their nominal power without any change in power during operation. However, each home appliance has its own unique features. In the energy demand estimation studies, investigating each instrument separately and on an hourly basis will provide more accurate estimations (Pipattanasomporn et al., 2014).

In this study, a general estimation method was adopted, and hourly consumption of household appliances was considered by considering their nominal power. These consumptions were analyzed for three households as mentioned before. Information was obtained from each household on how many hours a day 12 household appliances and lamps were used and which brand and model household appliances they owned. In line with this information, the load profile of approximately 3 persons was created by taking the average of three households.

3.3. Solar Data

The data of daily solar energy first became essential for agriculture and natural resources management. Cloud covers that limit crop production and block the sun are an important factor in agricultural areas. The status and quality of solar data has long been viewed as problematic. Even in places that study solar energy, there have been days when solar data is missing or outside of its expected range. The state of the sky is very important in collecting solar data. For example, radiation measurements are taken in large quantities in clear weather conditions. Measurement of solar data is still not easy even in today's conditions. Expensive, difficult to maintain and calibrate equipment is used for measurement such as pyranometers and pyreliometers. In addition, there is no organization that centralizes information at meteorological stations and is responsible for the calibration and accuracy of the sensors. The images that most efficiently solve the continuity problem and inconsistency in solar data come from polar orbiting or stationary satellites.

NASA provides meteorological and solar data from satellite information and modeling forecasts. Since 1983, the solar radiation data has been available and calculated. From 2008 to the present, different situations of the Fast Long Wave and Short-Wave Radiative Fluxes (FLASHFlux) project models have been used. These project models were used to predict solar data from CERES sensors used on the NASA satellites. CERES sensors, unlike others, measure solar radiation emitted and reflected from the Earth' s top of the atmosphere (Sayago et al., 2020).

In this study, solar data were taken according to the coordinates of the area where the hybrid system will be installed. It is taken from NASA POWER, where NASA's meteorological information is provided free of charge in line with these coordinates. These coordinates are 38.33 degrees latitude and 26.63 degrees longitude as mentioned before.

3.4. Wind Data

Many of instruments used for wind data are mounted on a mast. The purpose of this mast is to levitate the mounted instruments to measure the data in the surrounding or near area swept by the rotor in the wind turbine.

Basically, there are two types of masts: lattice and tubular mast. Tubular masts consist of a thin cylinder made of aluminum or steel. It is also lightweight and easier to plant. However, the tubular mast cannot go as high as the lattice mast. The lattice mast that can go higher is more difficult and costly to install, but once installed they are robust and considered suitable for longer term wind source measurement. Flow around the structure is disrupted in both tubular and lattice mast types, but this occurs more often with lattice masts. This disturbance occurs very close to the tower and means that it does not represent flow. To avoid this disturbance, instruments measuring wind speed and direction are not mounted directly on the mast, but rather on the boom outside the mast. There are many recommendations stating how far, in which direction, and how thick the boom should be from the mast, but what many people use is the one specified by the IEC.

After the mast is planted and the instruments mounted, the measurement process begins. This is called a measurement campaign. The measurement campaign is to measure over a long period of time, as well as data obtained represent what is desired to be known. The higher the mast, the better, because the main point of installing the mast is to measure wind speed ("Meteorology for Wind Energy," 2015).

In this study, the hybrid system will be installed near the IZTECH campus, it has been studied with real data. For this, the wind data between 09/04/2019-22/04/2020 were measured from the meteorological mast in the IZTECH campus and calculations were made accordingly. IZTECH meteorological mast seen in Figure 3.4 below.

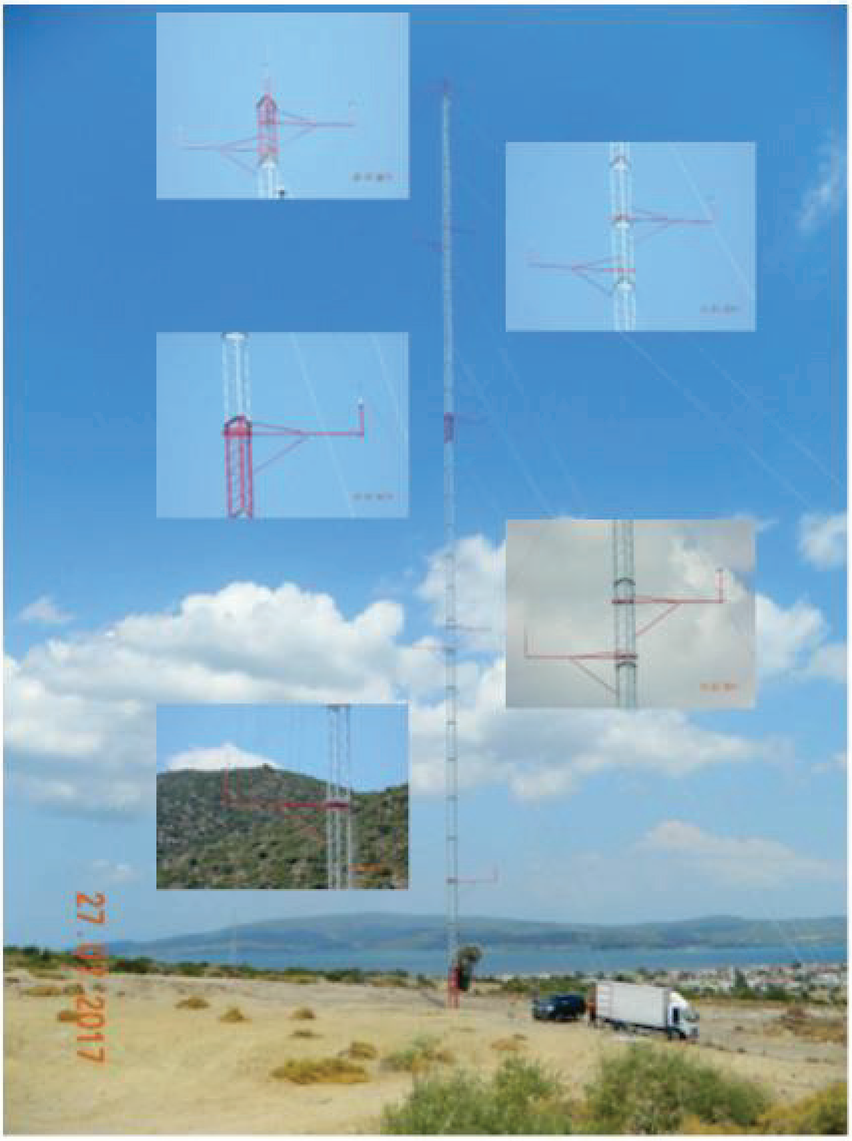


Figure 3.3 IZTECH meteorological mast (Source: Tuna, 2018)

CHAPTER 4

MODELING APPROACH

The system was designed to meet the electricity need of 50 households located at IZTECH campus while the energy need for heating and cooling was disregarded, and the study was carried out on the weather conditions of this field. Firstly, the consumption of 2 houses (4 people and 2 people) living within the boundary of this field was observed. The observed consumption was considered according to the yearly consumption of households and the consumption of their model averagely. The weather conditions of the IZTECH campus were obtained. The wind data were taken from the most up-to-date data recorded previously, and the date range of these data is between May 2019 and May 2020. Thereupon, the solar data were taken from NASA's official site by choosing the same dates to reach the most accurate results. The choice of PV panel and considering energy power were made by using Matlab/Simulink. As these calculations, different graphs were created for PV and wind yearly and hourly by using Matlab/Simulink. These created graphs were shown in a single graph together with the consumption. After these studies, the difference between the power of the wind and solar energy produced and the consumption results were examined and the decision to store the excess energy was taken. Lithium-ion was chosen as the battery. A method was created for this. This method shows us how many batteries and panels we should use, and under which conditions it will give the most optimal result economically.

4.1. Modeling Tools

In this study, MATLAB and Simulink were used for calculation, analysis, and modeling. Firstly, the PV panel and the battery were calculated with blocks available in the library of the Simulink program. MATLAB was used for code software and analysis.

MATLAB is a commercial tool that uses a developed mathematical method as calculation and includes tools such as Maple, MathCad, Mathematica. MATLAB is abridgment of Matrix Laboratory. Fundamentally, this tool can be called calculation machine. Therefore, usages of MATLAB are available for many engineering lectures. Thus, MATLAB is an ideal tool for many engineers and scientists. It has versions for usage of both students and professionals. Mostly, it is available on the computers of universities as licensed.

Another tool that was used in this project is Simulink. Simulink is a part of MATLAB package that models by using blocks as problem solutions. It is an ideal method to analyze the systems that are named as dynamics or changing according to time. Unlike MATLAB, Simulink analyzes mathematical calculations according to the time by modeling using blocks that can replace code ("MATLAB for Engineers," 2012).

4.2. Load Profile Generation

The annual load profile for households was developed based on the loads of three specific houses with an average of three people and the monthly overall energy consumption of houses. The former was determined by interviews with residents while the latter was taken from IZTECH Campus Energy Information Center. Only electricity consumption of houses was considered in this study. The heating and cooling related energy consumption were partly included since some houses uses air conditioner for heating and cooling while the other uses stoves. The electricity consumption of a house was calculated by information about the frequency and duration of houseware usage provided by residents for 3 houses and each house was assumed to consume same amount of electricity for each day during the year. The total daily electricity consumption of houses was adjusted in a way that the total monthly electricity consumption is the same with the data provided by IZTECH Campus. There are 50 buildings in IZTECH lodgings. The average consumption of the monthly lodging varies between 4000kWh and 5000kWh averagely.

4.3. PV Power Model

In this study, Simulink was first used for an example modeling. This example modeling is shown in Figure 3.3. TRNSYS program was used to calculate the production power. The data of the selected solar PV panel (LG405N2T-J5) was entered into this TRNSYS program, and the location of IZTECH lodgings was also entered into the program to calculate the production according to the field data. As a result, the production power from our PV panel was calculated hourly. TRNSYS program uses 5-parameter equivalent circuit model shown in Figure 4.1 proposed by Duffie and Beckman (1991). In the model the current-voltage characteristic of PV changes was determined depending on solar radiation and temperature as shown in the following equation:

$$I = I_L - I_O[\exp\left(\frac{q}{\gamma k T_c}(V + IR_s)\right) - 1] \tag{1}$$

where R_s is module resistance, g is PV curve fitting parameter, k is Boltzmann constant ($1.380622\text{x}10^{-23}$ J/K), q is electron charge ($1.602\text{x}10^{-19}$C), T_c is cell temperature, I_L is photocurrent and I_0 is the diode reverse saturation current. The latter two were calculated by using Eqn 2 and 3 as follows:

$$I_L = I_{L,ref}\frac{G_T}{G_{T,ref}} \tag{2}$$

$$I_0 = I_{0,ref}(\frac{T_C}{T_{C,ref}})^3 \tag{3}$$

The equation 1 above explains the current-voltage function. IL and lo values are found in other equations. The Newton method is used to calculate the PV current. In addition, a repetitive search process is carried out to find the voltage of the maximum power point on the current-voltage curve.

$$T_c = T_a + \frac{1-\frac{\eta_C}{\tau a}}{\frac{G_T \tau a}{U_L}} \tag{4}$$

where T_a is the ambient temperature (25°C), $\eta_c \eta c$ is the conversion efficiency of the module, $\tau a \tau a$ is module transmittance-absorptance product and $U_L UL$ is thermal loss coefficient. The latter two were determined by using the following equation:

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \tag{5}$$

where the radiation at NOCT (Nominal Operating Cell Temperature), $G_{T,NOCT}$ and the ambient temperature are 800 W/m2 and 20°C and the cell temperature at NOCT, $T_{c,NOCT}$, is available in the manufacturers catalog. When all equations were solved, the power output of PV module was calculated at maximum power point by Newtons method via iterative search.

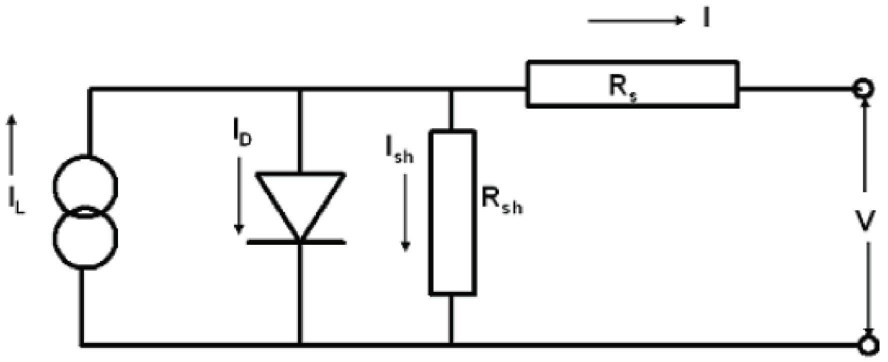


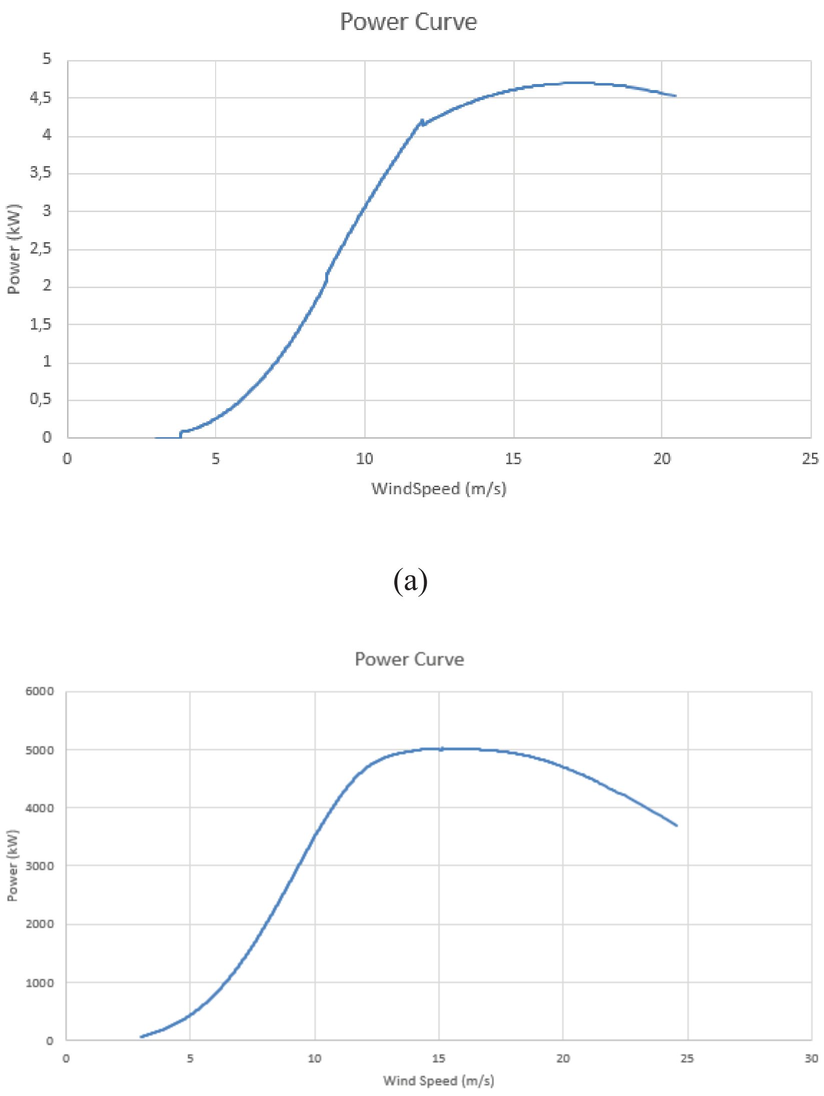
Figure 4.1 The electric circuit of PV Array Module in TRNSYS (Source: TRNSYS 18, 2018)

4.4. Wind Power Model

In this study, data obtained from the IZTECH meteorological mast was used since the hybrid system will be installed in an area close to IZTECH residences. Wind power was determined using data obtained from the meteorological mast. Specific wind turbines were selected for power calculations, namely Ryse Energy's 5 kW 27m and Gamesa's 5 MW 95-meter turbines. Power curves for these turbines were first drawn from their catalogs. The power output of the related wind turbines were calculated based on these plotted power curves and our own wind data. Since wind data obtained from the IZTECH meterological mast are available for specific altitude (10, 20, 30, 50, 100 m) and the wind speed at the rotor height of Ryse Energy's 5 kW (27 meter) and Gamesa's 5 MW (95-meter) were calculated by using the power law as follows:

Power Law Equation,

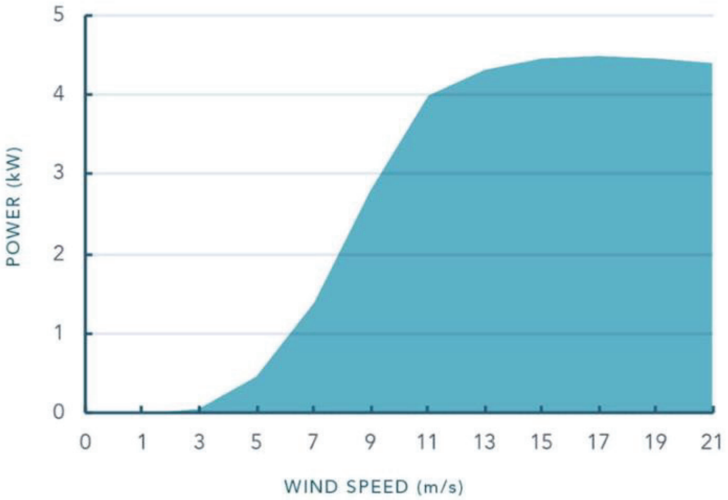
$$v = v_i\left(\frac{H}{H_i}\right)^{\alpha} \tag{6}$$



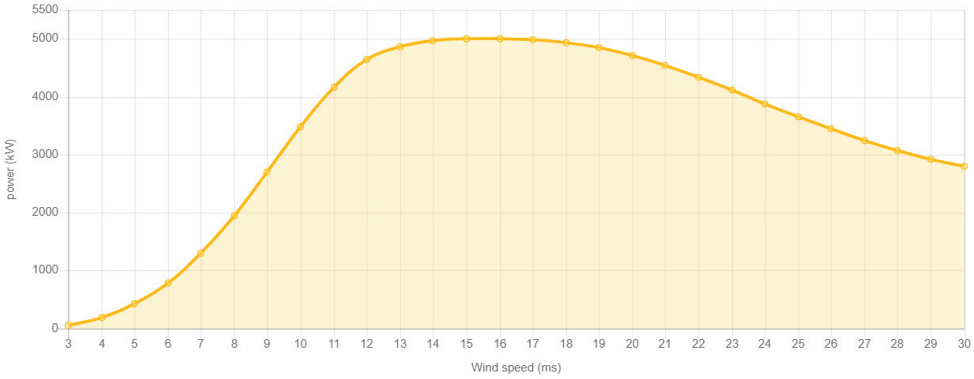
(a)

(b)

Figure 4.2 Power wind speed characteristics for 5kW wind turbine (a) and 5 MW wind turbine (b)



(a)

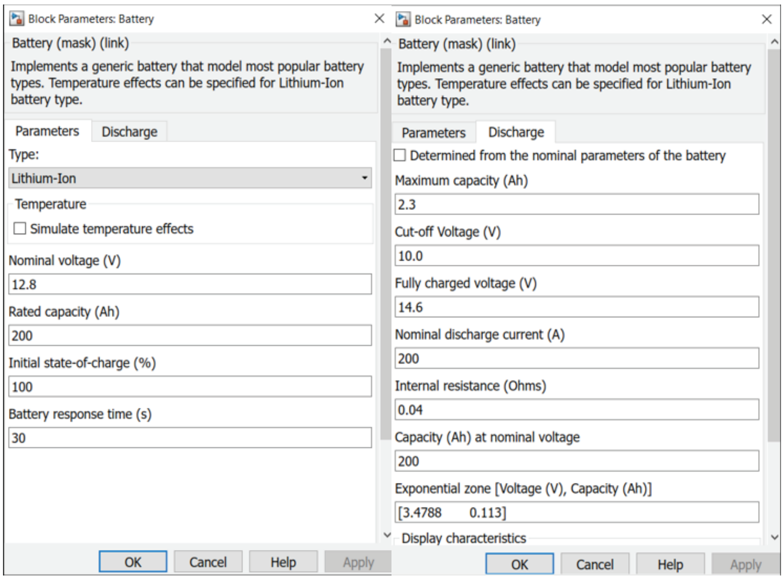


(b)

Figure 4.3 Power wind speed characteristics for Ryse Energy E-5 HAWT(a) and Gamesa G 128-5.5 MW (Source:URL2 https://www.ryse.energy/5kw-wind-turbines/, URL2: https://en.wind-turbine-models.com/turbines/767-gamesa-g128-5.0mw)

4.5. Optimization

For the optimization study, a house load graph, wind turbine power output and PV power output were calculated. After these calculations, the lithium-ion battery used for storage in renewable energy was selected. The most suitable battery to use in this system has been found to have its properties were used in Simulink Battery block. The selected battery has capacity of 2560Wh and nominal voltage of 12.8V. The characteristics of the Simulink Battery block and the information about the battery itself are shown in Figure 4.8. This information is included in the datasheet of the model selected for the battery (Bluetooth, n.d.).



Battery (mask) (link)

Implements a generic battery that model most popular battery types. Temperature effects can be specified for Lithium-Ion battery type.

Type: Lithium-Ion

Temperature

☐ Simulate temperature effects

Nominal voltage (V): 12.8

Rated capacity (Ah): 200

Initial state-of-charge (%): 100

Battery response time (s): 30

Battery (mask) (link)

Implements a generic battery that model most popular battery types. Temperature effects can be specified for Lithium-Ion battery type.

☐ Determined from the nominal parameters of the battery

Maximum capacity (Ah): 2.3

Cut-off Voltage (V): 10.0

Fully charged voltage (V): 14.6

Nominal discharge current (A): 200

Internal resistance (Ohms): 0.04

Capacity (Ah) at nominal voltage: 200

Exponential zone [Voltage (V), Capacity (Ah)]: [3.4788 0.113]

Figure 4.4 Simulink Battery block and specifications

As the calculation method for the optimization study of PV and Battery, reference was taken from Borowy et al.,1996. The calculation of the optimum number of PV panels and the number of batteries was based on the Loss of Power Supply Probability (LPSP). The LPSP was defined as the long-time average rate of load that cannot be covered by a system. If the power and storage from the PV panels produced by the wind turbine are exhausted, the load will not be covered. If the LPSP is 0, it means that the load will always be covered. If it is 1, it means that the load will never be covered (Borowy & Salameh, 1996).

Before proceeding to the calculations, the default values were taken as an example in the studies of Borowy et al.,1996, and this study was proceeded in the same way. For this, the efficiency of the inverter is assumed to be constant. Battery efficiency is also and return efficiency, and the efficiency is taken as 0.92 according to the characteristics of the selected battery. After these assumptions and acceptances, calculation methods were started. Formula was taken from Borowy et al., 1996, as previously mentioned.

When starting the calculations, the power produced will be calculated first. In this calculation, as mentioned the hourly production of a single wind turbine and the rest of the PV panel's number and hourly generated power were considered and this called Eg(t).

$$E_{G(t)} = E_{W(t)} + N_{PV} * E_{PV(t)} \tag{6}$$

where:

$E_{G(t)}$ = Generated power hourly (Wh),

$E_{W(t)}$ = The wind power output hourly (Wh),

$E_{PV(t)}$ = The PV panel power output hourly (Wh),

N_{PV} = The number of PV panel.

The definition of the expressions in the above formula is as follows. Ew(t) is the hourly generating power of the wind turbine, Epv(t) is hourly generating power of a panel, and Npv is the number of panels used. If the power generated from the wind turbine and PV panels exceeds the value of the load demand, the batteries will go into storage. This expression is expressed in the following equation.

$$E_{B(t)} = E_{B(t-1)} + \left(E_{G(t)} - \frac{E_{L(t)}}{\eta_{inv}}\right) * \eta_{batt,in} \tag{7}$$

where:

$E_{B(t)}$ = Energy stored hourly in batteries,

$E_{B(t-1)}$ = Energy stored in previous hour,

$E_{L(t)}$ = Load demand hourly (Wh)

η_{inv} = The efficiency of inverter,

$\eta_{batt,in}$ = The round-trip efficiency of the batteries.

$E_{B(t)}$ is the energy stored in the battery at t hour, $E_{B(t-1)}$ is the energy stored in the battery in the previous hour, E_L is the load demand at t, N_{batt} is the round-trip efficiency of the battery, and η_{inv} is the inverter's efficiency.

As mentioned above, the equation shows the time when the generation power is more than the load demand. The situation that will be mentioned now is the unloading situation if the demand is more than the generation power. The equation explaining this expression is shown below.

$$E_{B(t)} = E_{B(t-1)} - (\frac{E_{L(t)}}{\eta_{inv}} - E_{G(t)}) \tag{8}$$

As a result of these formulas, the loss power supply can (LPS) can be calculated. This expression is also shown in the equation below.

$$LPS_{(t)} = E_{L(t)} - \left(E_{G(t)} + E_{B(t-1)} - E_{Bmin}\right) * \eta_{inv} \tag{9}$$

The power supply loss probability (LPSP) is also found by dividing the LPS sums at the t by the totals for the load demand at time t. The equation that expresses this is given below.

$$LPSP(Nbatt, Npv) = \frac{\sum_{t=1}^{T} LPS_t}{\sum_{t}^{T} E_{L(t)}} \tag{10}$$

A flowchart diagram was created to calculate the LPSP value. This diagram was created as an example from Borowy et al.,1996. MATLAB was used to create diagram of this flowchart. Figure 4.9 shows the flowchart diagram.

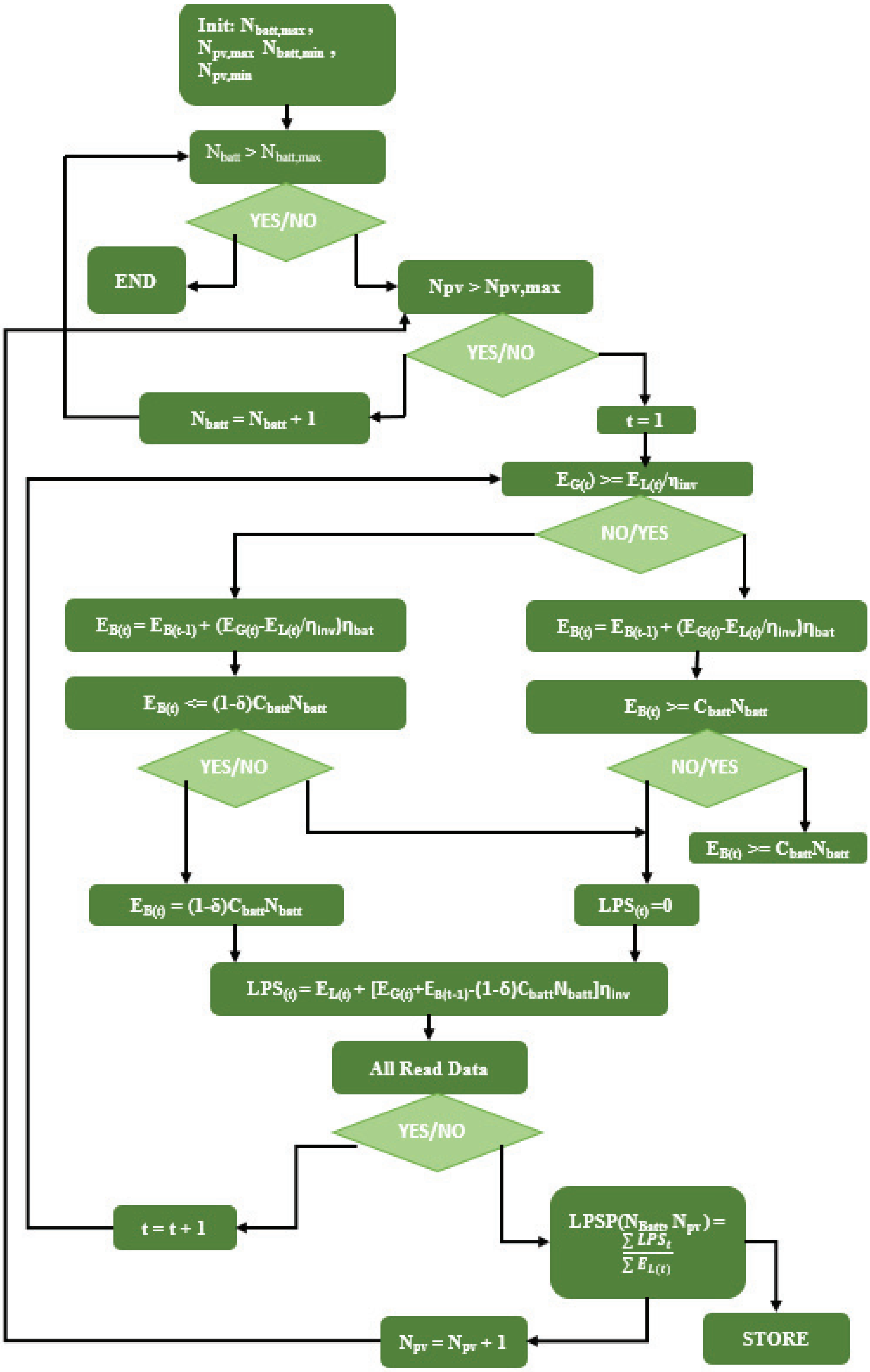


Figure 4.5 Flowchart Diagram

Since this study will also be considered from economic point of view, the models of each component were determined separately, and the average sales prices were found.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Annual Load Profile

As mentioned in Chapter 3, the load data taken from IZTECH lodgings and real data. Its annual load graph is extracted from MATLAB/Simulink. This chart gives the load profile between 09/05/2019-22/04/2020 as shown in Figure 5.1 below and the total hours are determined as 8384. As can be seen in figure, the load started to increase in about a year. This is an indication of an increase in consumption. For this, we can think that the use of household appliances has increased or that it is due to increase in the number of technological appliances. The electricity consumption is high at specifically winter times since the heating requirements was partially fulfilled by air conditioners at the related months. Also, you may see monthly load profiles in Figure 5.2. Figure 5.3 show daily consumption on May 9, 2019. As seen in figure, consumption increases in the evening hours. Thus, we can predict from this graph that householders go home after school or work. Besides, there is an increase in the afternoon hours. We can think that the reason for this is going home from university for lunch at noon.

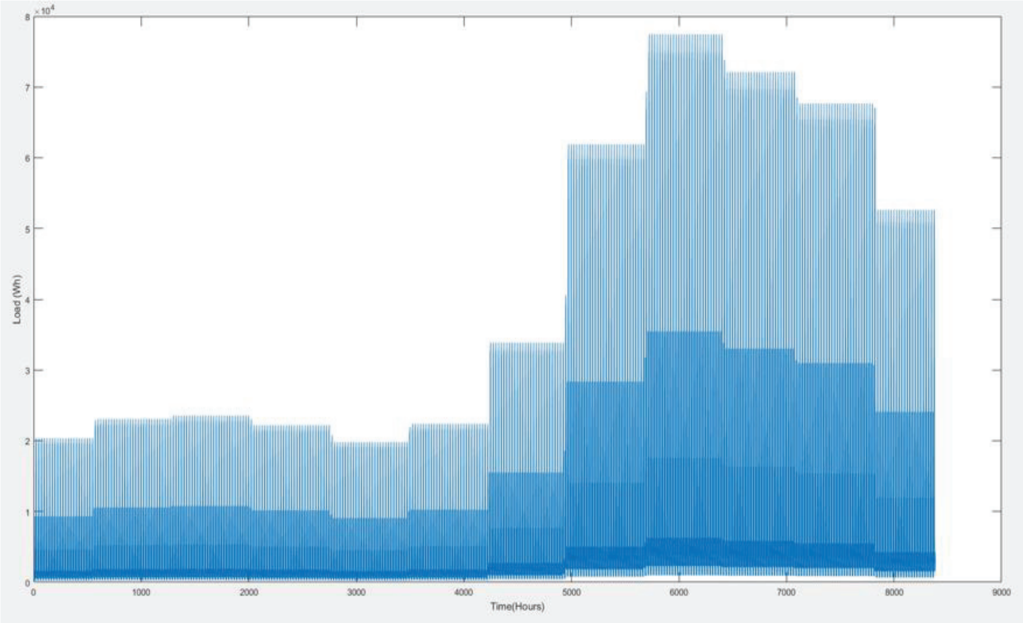


Figure 5.1 Annual Load Profile of IZTECH Lodgings

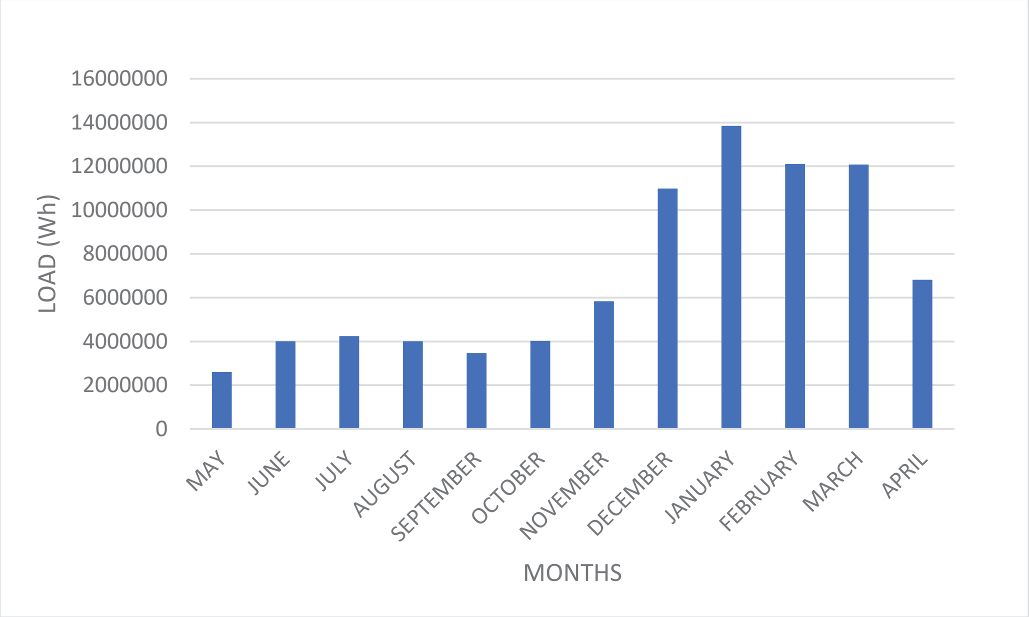


Figure 5.2 Monthly consumption

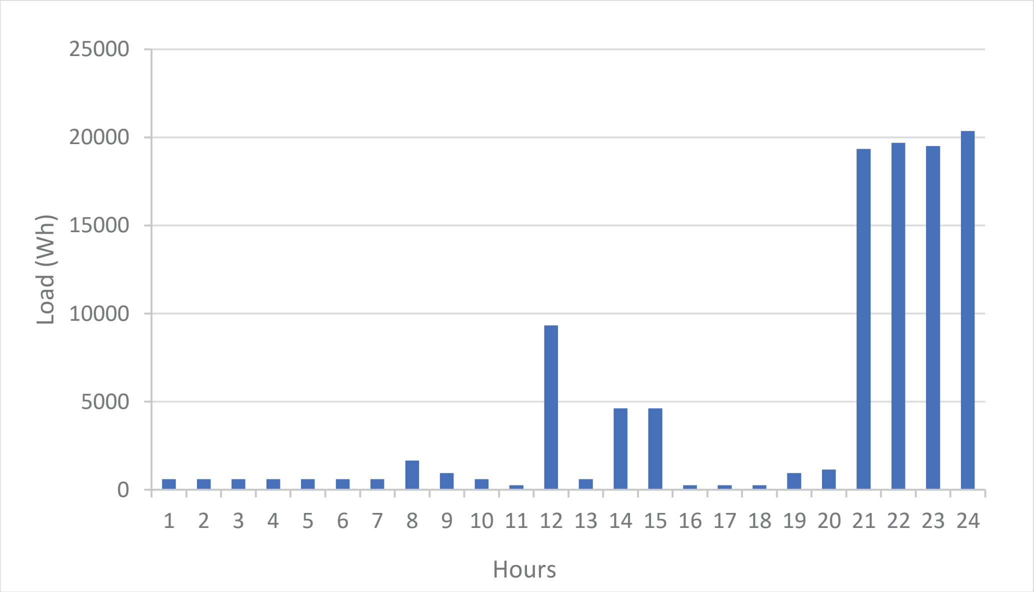


Figure 5.3 9 May 2019 Daily consumption

5.2. Annual PV Power Output

Considering the PV module mentioned in Chapter 4, it was found how much a single panel produces according to the data received from NASA POWER, depending on the conditions of the place where the hybrid system will be installed. The graph of production of this single panel is shown in Figure 5.4 below. This chart was created in MATLAB/Simulink. The lowest data seen in the graph corresponds to the winter months. This is because the irradiance value taken from the sun is low in these months. The highest data is observed in July and August. When we look at some days, high and low values are found, the reason for this is that the high values show us the sunshine hours of the day. The lower values are the evening hours that do not get sun.

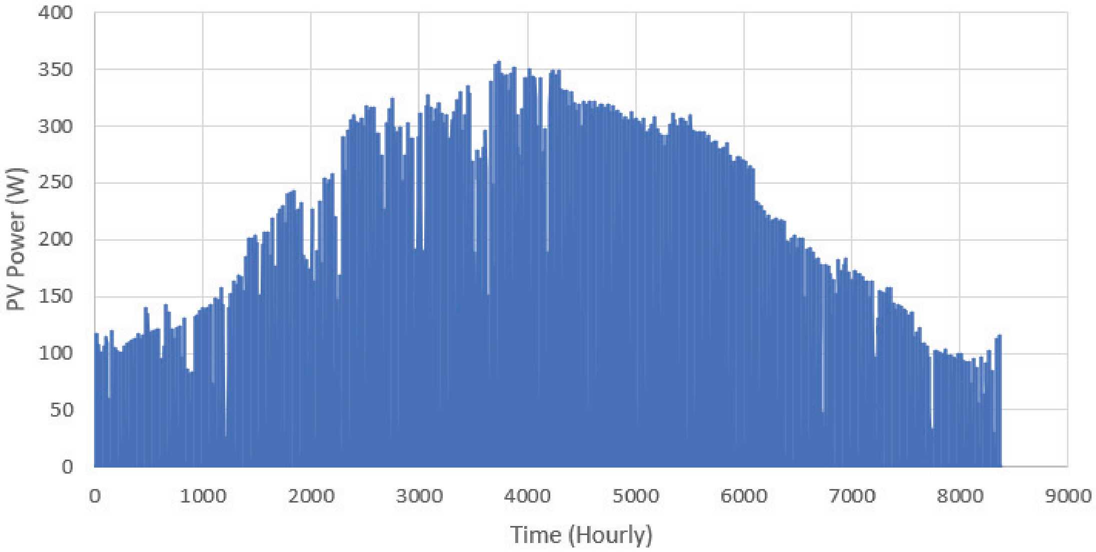


Figure 5.4 Annual PV Power Output

5.3. Annual Wind Power Output

The data for calculating the power output of the wind turbine were taken from the IZTECH meteorological mast as mentioned in Chapter 3. With these data based on the wind power calculations in Chapter 4, the annual wind power graph was created in MATLAB/Simulink. This graph is shown in Figure 5.5.

As seen in Figure 5.3, some hours the wind data is at its maximum value and in some places, it is at minimum values. This is due to the annual wind speed graph shown in Chapter 4. The results at the maximum values tell us that the wind should be between 12 and 25 m/s. The low results also indicate that the wind speed is low. In cases where the wind power is 0, the wind speed is lower than the initial speed of the wind turbine. For this reason, the wind turbine does not work and gives us 0 as output power.

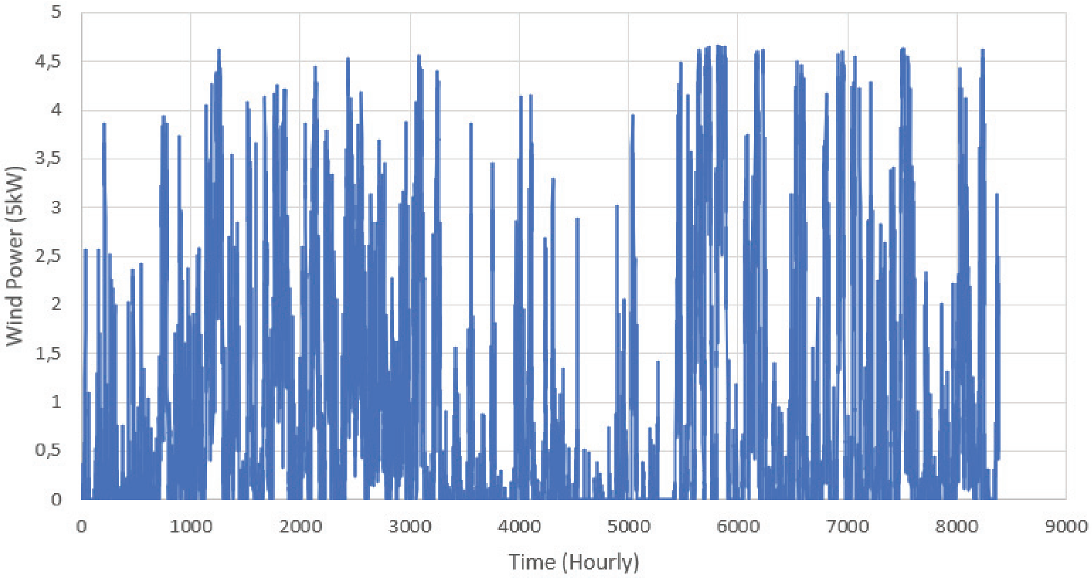


Figure 5.5 Annual Wind Power Output

5.4. Optimization of PV+Battery+Wind System

As the calculation method for the optimization study of PV and Battery, reference was taken from Borowy et al.,1996.

Before proceeding to the calculations, the default values were taken as an example in the studies of Borowy et al.,1996, and this study was proceeded in the same way. For this, the efficiency of the inverter is assumed to be constant. Battery efficiency is also and return efficiency, and the efficiency is taken as 0.92 according to the characteristics of the selected battery. After these assumptions and acceptances, calculation methods were started. Formula was taken from Borowy et al., 1996, as previously mentioned.

When starting the calculations, the power produced will be calculated first. In this calculation, as mentioned the hourly production of a single wind turbine and the rest of the PV panel's number and hourly generated power were considered and this called $E_{G(t)}$.

A flowchart diagram was created to calculate the LPSP value. This diagram was created as an example from Borowy et al.,1996. MATLAB was used to create diagram of this flowchart.

Before proceeding to the code and software of the flowchart, first, the maximum number of batteries and the maximum number of PV panels in the flowchart must be found. First, hourly power outputs from a panel and an additional turbine are summed up to 8384 hours, and load demands are also summed up. When the total of the load demand is divided by total of the generated power, the maximum number of panels is found. Similarly, the maximum number of batteries is found. As a result of these processes, the maximum number of PV panels was 200, and the maximum number of batteries was 50. After, the maximum values were found, the code of the above-mentioned flowchart diagram in Figure 5.5 was created in MATLAB. As a result of these operations, LPSP values were found, and a graph was created accordingly.

In this study, different cases are discussed depending on LPSP study at the same time. A 5MW wind turbine and battery are used in this hybrid system. Secondly, only PV panels and batteries are used in this project.

Figure 5.6 shows the graph created according to the number of batteries, the number of PV panels and the LPSP value. The number of PV panels and the number of batteries versus LPSP values are shown in Table 5.1. The number of batteries and a 5MW wind turbine versus LPSP value are shown in Table 5.2. Also, the number of PV panels and the number of batteries versus LPSP values for a 5kW wind turbine are shown in Table 5.3.

The intersection points of the two curves in the graph was the optimum value of the PV and battery numbers.

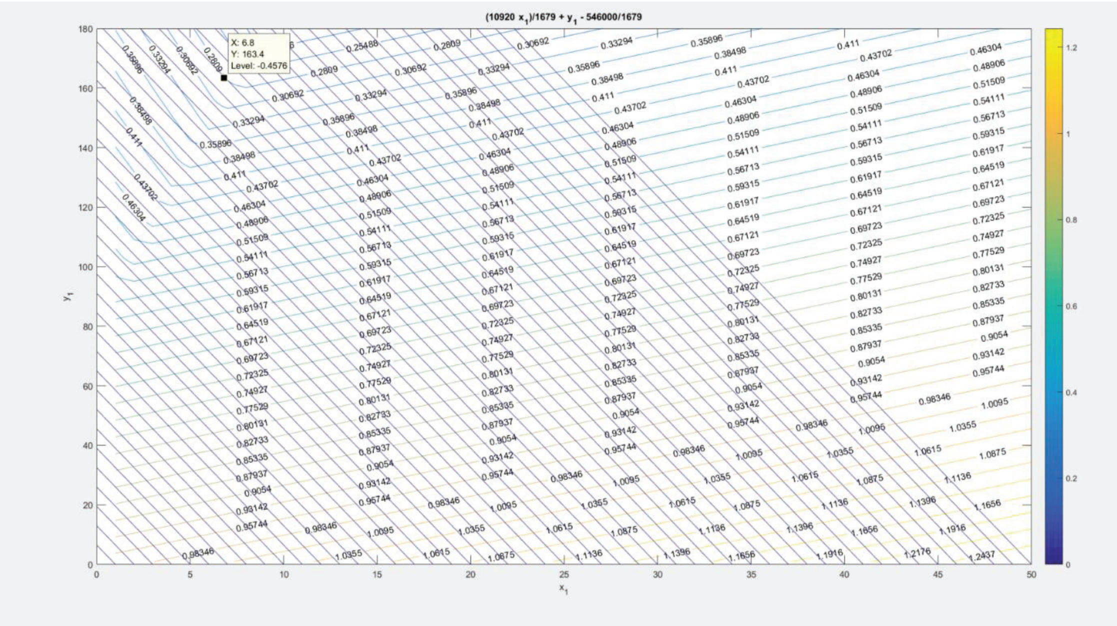


Figure 5.6 The graphics of the number of PV panels versus the number of batteries for a given LPSP

Table 5.1 The number of PV and the number of batteries versus LPSP values

LPSP	Npv	Nbatt
0.2809	163	7
0.3589	144	5
0.4372	126	3

Table 5.2 The number of batteries and a 5MW wind turbine versus LPSP value

LPSP	Ntur	Nbatt
0.0031	1	6

Table 5.3 The number of PV panels and the number of batteries versus LPSP values for a 5kW wind turbine

LPSP	Npv	Nbatt
0.083567	195	12
0.12202	185	11
0.14175	181	10
0.24038	153	7
0.45737	101	1

The economic study was made according to the LPSP results. The Levelized Cost of Energy was used as method of economic study.

We can call the concept of payback in energy systems the levelized cost of energy or LCOE. Instead of compensating for the initial investment, LCOE determines how much money the system needs to earn per unit of electricity (such as kWh, MWh, etc., or other types of energy) to compensate for its lifetime costs. This includes maintenance costs, operating costs, and capital investments.

LCOE is one of the ways a company determines whether or not to proceed with a project. To determine LCOE, a company must know necessary parameters such as the system's lifetime, the electricity it will generate, and input costs (Lai & McCulloch, 2017).

i) An important measure of the cost of producing energy is the Levelized Cost of Energy, LCOE.

ii) It is defined as the PV of all project costs over the project life cycle, divided by the PV of all energy production during the same period.

iii) Commonly used to compare the efficiency of different energy production methods (Lai & McCulloch, 2017).

$$LCOE = \frac{PV\ of\ costs}{PV\ of\ energy\ production} = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+i)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+i)^n}} \tag{10}$$

where:

C_n = Total initial costs

i = Minimum attractive rate of return

n = year

E_n = Mean of energy production

The calculations are performed according to this number of PVs and batteries by using Excel worksheet and tabulated as Table 5.2, Table 5.3, and Table 5.4. The calculation in the tables below includes the number of batteries and PVs according to LPSP values. According to these numbers, total initial cost and the power produced were calculated and the LCOE value was found accordingly. Together with the total initial cost, the annual costs of each component were also considered for each year. In addition to these costs, the cost of energy taken from the grid equal to the value found for LPSP was added. Electricity received from the grid is 0,1049 $/kWh ("Republic of Turkey Energy Market Regulatory Authority", EPDK). The mean power produced by these components was added with these calculations. When these values were calculated according to the equation above, the LCOE value was found. Minimum attractive rate of return was taken as 8,46% (Fonu, 2022). The cost of solar PV panels can vary depending on factors such as the type and size of the panel, as well as the location and market conditions. According to a report by the National Renewable Energy Laboratory (NREL), the average cost of solar panels installed in the United States in 2020 was $2.81 per watt for residential installations and $1.93 per watt for utility-scale installations. This means that a typical 5 kW residential solar PV system would have an initial cost of around $14,050.

It's important to note that the cost of solar panels has been decreasing over time due to improvements in technology and increased market competition. In fact, the cost of solar panels has dropped by over 70% since 2010, according to the same NREL report. (National Renewable Energy Laboratory (NREL). (2021). U.S. Solar Photovoltaic System Cost Benchmark: Q1 2021. (URL3:https://www.nrel.gov/docs/fy21osti/79181.pdf/2021)

The operating and maintenance (O&M) costs of solar PV panels can vary depending on factors such as the location, system design, and the level of maintenance required. According to a study by the National Renewable Energy Laboratory (NREL), the typical annual O&M cost for a residential solar PV system in the United States ranges from $15 to $30 per kW, while the typical annual O&M cost for a utility-scale system ranges from $5 to $20 per kW. This means that a typical 5 kW residential solar PV system would have an annual O&M cost of around $75 to $150.

The cost of a LiFePO4 battery can vary depending on the brand, capacity, and other factors. However, according to a report by BloombergNEF, the average price of a LiFePO4 battery pack in the first half of 2021 was $137 per kWh.

Assuming a 12.8V/200Ah LiFePO4 battery pack with a usable capacity of around 80% (160Ah), the total energy capacity of the battery would be approximately 2.05 kWh. Multiplying this by the average price of $137 per kWh would give an estimated initial cost of around $281 for the LiFePO4 battery pack.

It's worth noting that the price of LiFePO4 batteries has been decreasing over time, and this trend is expected to continue as the technology improves and production scales up. (BloombergNEF. (2021). Lithium-ion battery price survey. (URL4: https://about.bnef.com/lithium-ion-battery-price-survey/2021).

As mentioned above, LCOE and net present value (NPV) methods were used for economic analysis in this project. The levelized cost of energy (LCOE) by considering the initial capital cost (CAP), annual O&M cost (O&M), fixed charge rate (F), and salvage value (R). (Mittal & Singh, 2021).

The LCOE formula is:

LCOE = (CAP + (O&M x n) + (F x CAP)) / E

Firstly, to calculate the LCOE of the solar PV panel and LiFePO4 battery system when 28% of the average consumption is taken from the grid, we need to adjust the total lifetime energy output (E) accordingly.

The total energy consumption from the solar PV panels and LiFePO4 batteries is:

E_system = (1 - 0.28) x 83,909 kWh/year = 60,330.57 kWh/year

The total energy output of the solar PV panels and LiFePO4 batteries over the project lifetime is:

E = E_system x 20 years = 1206611.42 kWh

We need to calculate the levelized cost of energy (LCOE) by considering the initial capital cost (CAP), annual O&M cost (O&M), fixed charge rate (F), and salvage value (R). Let's assume that the initial capital cost for the system is $2.425,03, sum of annual O&M cost is $990,18, fixed charge rate is 10.83%.

The LCOE formula is:

LCOE = (CAP + (O&M x n) + (F x CAP)) / E

where n is the project lifetime in years.

Substituting the given values, we get:

LCOE = ($2.425,03 + ($990,18 x 20) + (0.1083 x $2.425,03)) / 60,330.57 kWh

LCOE = $0.02/kWh

Since 28% of the energy consumption is taken from the grid and the electricity charge from the grid is $0.1049 $/kWh, the effective LCOE for the system is:

Effective LCOE = (0.72 x $0.02/kWh) + (0.28 x $0.1049/kWh)

Effective LCOE = $0.04/kWh

Table 5.4 LCOE Value for LPSP 0.281

163x405W PV + 7x12,8V/200Ah Battery **(LPSP=0.281)**

PV	Residential installations ($/W)		$2,81	$458,03
n=20	O&M ($/kW)		$15,00	$990,00
Battery	Initial Cost ($/kW)		$ 138,00	$2.472,00
	O&M ($/kWh)		$0,01	$0,18
		Consumption		
E_system =	0,719	83.909	60330,57	kWh/year
Total Energy output E=	1206611,42	kWh		
CAP	$2.930,99			
O&M*n	$19.803,58			
F	11%			
LCOE	$0,02			
Effective LCOE	$0,04			

Table 5.5 LCOE Value for LPSP 0.359

144x405W PV + 5x12,8V/200Ah Battery **(LPSP=0.359)**

PV	Residential installations ($/W)		$2,81	$404,64
	O&M ($/kW)		$15,00	$874,80
Battery	Initial Cost ($/kW)		$ 138,00	$1.766,40
	O&M ($/kWh)		$0,01	$0,13
		Consumption		
E_system =	0,641	83.909	53785,67	kWh/year
Total Energy output E=	1075713,38	kWh		
CAP	$2.171,04			
O&M*n	$17.498,56			
F	11%			
LCOE	$0,02			
Effective LCOE	$0,05			

Table 5.6 LCOE Value for LPSP 0.437

126x405W PV + 3x12,8V/200Ah Battery **(LPSP=0.437)**

PV	Residential installations ($/W)		$2,81	$354,06
	O&M ($/kW)		$15,00	$765,45
Battery	Initial Cost ($/kW)		$ 138,00	$1.059,84
	O&M ($/kWh)		$0,01	$0,08
		Consumption		
E_system =	0,563	83.909	47240,77	kWh/year
Total Energy output E=	944815,34	kWh		
CAP	$1.413,90			
O&M*n	$15.310,54			
F	11%			
LCOE	$0,02			
Effective LCOE	$0,06			

Table 5.7 LCOE Value for LPSP 0.0031

1x5MWTurbine + 6x(12,8V/200Ah Battery) **(LPSP=0.0031)**

Turbine	Residential installations ($/kW)		$6.500.000,00	
	O&M ($/kW)		$45.061,18	
Battery	Initial Cost ($/kW)		$ 138,00	$2.119,68
	O&M ($/kWh)		$0,01	$0,15
		Avarage Consumption		
E_system =	0,9969	83.909	83648,8821	kWh/year
Total Energy output E=	1672977,642	kWh		
CAP	$6.500.138,00			
O&M*n	$901.226,74			
F	11%			
LCOE	$4,84			
Effective LCOE	$4,83			

Table 5.8 LCOE Value for LPSP 0.082567

1x5kWTurbine + 195x 405W PV + 12x12,8V/200Ah Battery **(LPSP=0.082567)**

Turbine	Residential installations ($/kW)		$15.000,00	$135.000,00
	O&M ($/kW)		$1.500,00	
Battery	Initial Cost ($/kW)		$ 138,00	$4.239,36
	O&M ($/kWh)		$0,01	$0,15
PV	Residential installations ($/W)		$2,81	$547,95
n=20	O&M ($/kW)		$15,00	$1.184,63
		Consumption		
E_system =	0,917433	83.909	76980,8856	kWh/year
Total Energy output E=	1539617,712	kWh		
CAP	$139.787,31			
O&M*n	$53.695,57			
F	11%			
LCOE	$0,14			
Effective LCOE	$0,13			

Table 5.9 LCOE Value for LPSP 0.12202

1x5kWTurbine + 185x 405W PV + 11x12,8V/200Ah Battery **(LPSP=0.12202)**

Turbine	Residential installations ($/kW)		$15.000,00	$135.000,00
	O&M ($/kW)		$1.500,00	
Battery	Initial Cost ($/kW)		$ 138,00	$3.886,08
	O&M ($/kWh)		$0,01	$0,15
PV	Residential installations ($/W)		$2,81	$519,85
n=20	O&M ($/kW)		$15,00	$1.123,88
		Consumption		
E_system =	0,87798	83.909	73670,42382	kWh/year
Total Energy output E=	1473408,476	kWh		
CAP	$139.405,93			
O&M*n	$52.480,57			
F	11%			
LCOE	$0,14			
Effective LCOE	$0,14			

Table 5.10 LCOE Value for LPSP 0.14175

1x5kWTurbine + 181x 405W PV + 10x12,8V/200Ah Battery **(LPSP=0.14175)**

Turbine	Residential installations ($/kW)		$15.000,00	$135.000,00
	O&M ($/kW)		$1.500,00	
Battery	Initial Cost ($/kW)		$138,00	$3.532,80
	O&M ($/kWh)		$0,01	$0,15
PV	Residential installations ($/W)		$2,81	$508,61
n=20	O&M ($/kW)		$15,00	$1.099,58
		Consumption		
E_system =	0,85825	83.909	72014,89925	kWh/year
Total Energy output E=	1440297,985	kWh		
CAP	$139.041,41			
O&M*n	$51.994,57			
F	11%			
LCOE	$0,14			
Effective LCOE	$0,14			

Table 5.11 LCOE Value for LPSP 0.24038

1x5kWTurbine + 153x 405W PV + 7x12,8V/200Ah Battery **(LPSP=0.24038)**

Turbine	Residential installations ($/kW)		$15.000,00	$135.000,00
	O&M ($/kW)		$1.500,00	
Battery	Initial Cost ($/kW)		$138,00	$2.472,96
	O&M ($/kWh)		$0,01	$0,15
PV	Residential installations ($/W)		$2,81	$429,93
n=20	O&M ($/kW)		$15,00	$929,48
		Consumption		
E_system =	0,75962	83.909	63738,95458	kWh/year
Total Energy output E=	1274779,092	kWh		
CAP	$137.902,89			
O&M*n	$48.592,57			
F	11%			
LCOE	$0,16			
Effective LCOE	$0,15			

Table 5.12 LCOE Value for LPSP 0.45737

5kWTurbine + 101x 405W PV + 1x12,8V/200Ah Battery **(LPSP=0.45737)**

Turbine	Residential installations ($/kW)	$15.000,00	$135.000,00
	O&M ($/kW)	$1.500,00	

Battery	Initial Cost ($/kW)	$138,00	$353,28
	O&M ($/kWh)	$0,01	$0,15

PV	Residential installations ($/W)		$2,81	$283,81
n=20	O&M ($/kW)		$15,00	$613,58
		Consumption		
E_system =	0,54263	83.909	45531,54067	kWh/year
Total Energy output E=	910630,8134	kWh		

CAP	$135.637,09
O&M*n	$42.274,57
F	11%
LCOE	$0,21
Effective LCOE	$0,16

Looking at the above results, it can be seen that the PV panel is more cost-effective than the wind turbine. The LCOE values increase due to the cost of the wind turbine. Therefore, the use of PV panels and batteries can be considered ideal for this system. Looking at the results, it can be seen that the use of renewable energy is advantageous both in terms of cost and environmental factors. It is expected that the LCOE values will not change much when only obtained from the grid. Therefore, these results appear to be inspiring for the future.

CHAPTER 6

CONCLUSION

Nowadays, the consumption of fossil fuels has increased due to the development of technology and the increase in the World population. The increase in the consumption of fossil fuels has started to cause an energy crisis in the World. However, with the increase in this consumption, it has become inevitable to increase the factors such as environmental pollution. Thus, the damage caused by fossil fuels to the environment and decrease in these resources have led many scientists to renewable energy resources. Because of this orientation, it was hoped that the energy crisis would be eliminated, and environmental pollution would decrease with it.

Many researchers have started to research on renewable energy sources. As a result of these research, good results have enabled investors to turn to renewable energy sources. Because of this renewable energy, it is aimed to eliminate electricity generation and heating problems. Today, solar and wind are among the most used renewable energy sources. The fact that solar and wind resources are continuous and therefore the production power is high having attractive the attention of people. In this way, there is a lot of research and studies for these resources. Many researchers are working on renewable energy sources to obtain more production power at less cost.

During the efforts to increase the production power of renewable energy sources, excess energy has drawn attention. Recently, there has been a concentration on this energy and a lot of execution has occurred. Thus, thoughts on storing this excess energy with batteries and using it later have occurred. In this way, it is seen that systems in which more than one renewable energy sources are used, which we call hybrid systems, occur.

This study is about the hybrid system and studied on power generation, storage, and economic analysis. This hybrid system includes solar, wind and battery. The aim of the study is to meet the electricity consumption of Izmir Institute of Technology (IZTECH) lodgings with renewable energy sources. According to these consumptions, the excess energy will be stored. An economic analysis was then made for this hybrid system. For this reason, it is aimed to install the system on the area near the IZTECH campus. To start the study, firstly, wind data were obtained from the meteorological mast belonging to IZTECH. Then, solar data were obtained according to the coordinates of the area. With these information, models of wind turbine, solar panel and battery were selected. A 5kW wind turbine, a 405W panel, and a 2560Wh battery were selected. Firstly, the annual power generation of the wind turbine was obtained. Secondly, the power generation of the solar panel was obtained with TRNSYS 18. Thus, sample hybrid systems modeling was created in MATLAB/Simulink.

With obtained power, economic analysis studies were started. This economic analysis study was based on the number of PV panels, wind turbines, and batteries. Therefore, a flowchart diagram was created depending on the number of the wind turbine, PV panel and battery. This flowchart diagram leads us to the Loss of Power Supply Probability. This flowchart diagram was calculated hourly for a year and was created in MATLAB.

The first economic optimization study was on the LPSP value found according to the number of PV panels and the number of the batteries. It was assumed to be a single wind turbine. With these calculations, the number of PV panels and the number of the batteries were found according to 3 different LPSP values. For these 8 different results, the Levelized Cost of Energy was calculated economically.

Table 6.1 The representation of LCOE and NPV values according to LPSP values.

LPSP	Number of PV	Number of Battery	Number of Wind Turbine	LCOE($/kWh)	NPV ($)
0.281	163	7	0	0.04	2.120.675,17
0.359	144	5	0	0.05	8.520.437,81
0.437	126	3	0	0.06	6.530.077,69
0.082567	195	12	1	0.13	17.493.770,51
0.12202	185	11	1	0.14	15.916.659,73
0.14175	181	10	1	0.14	15.235.267,73
0.24038	153	7	1	0.14	11.483.916,61
0.45737	101	1	1	0.16	5.517.247,16

The lowest LCOE value was determine as 0.04 $/kWh for the PV-battery system with LPSP value of 0.28. The related price is much lower than the grid electricity price of Turkey in 2022 (0.1049 $/kWh) indicating that the suggested PV-battery system is economically attractive. For the PV-battery system it was also seen that LCOE values increases with LPSP values (i.e., grid dependency) suggesting that off-grid PV-battery systems are economically more feasible than on-grid systems. The results also showed that when the PV-battery system is combined with a 5 kW wind turbine, the LCOE of the system increases to 0.13-0.16 $/kWh indicating that the addition of the wind turbine to the system affects the system economy negatively. This is attributed to the high initial cost of wind turbine.

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APPENDICES

APPENDIX A: Matlab Code

The Number of PV Panels and Batteries

```
clear all;

Npv_max      = 200;
Nbatt_max    = 50;
Cbatt        = 2560; % Battery capacity, Wh

load simdata

 Ew  = xlsread('veriler.xlsx', 'Sayfa1', 'Z:Z'); % Wind, Wh
 Epv = xlsread('veriler.xlsx', 'Sayfa1', 'S:S'); % PV, Wh
 El  = xlsread('veriler.xlsx', 'Sayfa1', 'F:F');  % Load,
Wh

%save simdata Ew Epv El

El_total         = sum(El);
n_data           = length(Ew);
eff_inv          = 1;
eff_batt         = 0.92;
delta            = 0.8;
LPSP             = -100 * ones(Nbatt_max,Npv_max);

for Nbatt = 1:Nbatt_max
    Nbatt;
    for Npv = 1:Npv_max
        clear LPS Eg Eb
        for t = 1:n_data
            Eg(t) = Epv(t) * Npv; % Total generation at
time 't'
            if t==1
                Eb0 = Cbatt;
            else
                Eb0 = Eb(t-1);
            end

            if Eg(t)>= El(t)/eff_inv

                Eb(t)   = Eb0 + (Eg(t)-
El(t)/eff_inv)*eff_batt;

                if Eb(t) >=Cbatt*Nbatt
                    Eb(t) =Cbatt*Nbatt;
                end
```

```
                LPS(t) = 0;
            else
                Eb(t) = Eb0-(El(t)/eff_inv-Eg(t));
                if Eb(t) <=(1-delta) * Cbatt * Nbatt
                    Eb(t) = (1-delta) * Cbatt * Nbatt;
                    LPS(t) = El(t)-(Eg(t)+Eb0-(1-
delta)*Cbatt*Nbatt)*eff_inv;
                else
                    LPS(t) = 0;
                end
            end
        end
        LPSP(Npv,Nbatt) = sum(LPS)/El_total;
    end
end
[C,h] = contour(LPSP,40);
clabel(C,h)
colorbar

 PV_cost     = 335.8;
 batt_cost   = 2184;
 slope = - batt_cost/PV_cost;
 x = 1:Nbatt_max;
% % x = 1:Npv_max;
 y = slope * x;
 hold on;
% for k=1:50
% plot(x,y+(k-1)*50,'k')
% end
% %plot(x,y+275,'k')
% ylim([0 Npv_max])

syms x1 y1
for l=1:50
ezplot(y1-slope*(x1-x(l)),[0 50 0 200])
hold on
end
```

The Number of Wind Turbines, PV Panels and Batteries

```
clear all;

Npv_max     = 200;
Nbatt_max   = 50;
Cbatt       = 2560; % Battery capacity, Wh

load simdata

 Ew  = xlsread('veriler.xlsx', 'Sayfa1', 'Z:Z'); % Wind, Wh
 Epv = xlsread('veriler.xlsx', 'Sayfa1', 'S:S'); % PV, Wh
 El  = xlsread('veriler.xlsx', 'Sayfa1', 'F:F');  % Load,
Wh

%save simdata Ew Epv El

El_total        = sum(El);
n_data          = length(Ew);
eff_inv         = 1;
eff_batt        = 0.92;
delta           = 0.8;
% LPSP            = -100 * ones(Nbatt_max,Npv_max);

for Nbatt = 1:Nbatt_max
    Nbatt;
    for Npv = 1:Npv_max
        clear LPS Eg Eb
        for t = 1:n_data
            Eg(t) =  Ew(t) + Epv(t) * Npv; % Total
generation at time 't'
            if t==1
                Eb0 = Cbatt;
            else
                Eb0 = Eb(t-1);
            end

            if Eg(t)>= El(t)/eff_inv

                Eb(t)  = Eb0 + (Eg(t)-
El(t)/eff_inv)*eff_batt;

                if Eb(t) >=Cbatt*Nbatt
                    Eb(t) =Cbatt*Nbatt;
                end
                LPS(t) = 0;
            else
                Eb(t) = Eb0-(El(t)/eff_inv-Eg(t));
                if Eb(t) <=(1-delta) * Cbatt * Nbatt
                    Eb(t) = (1-delta) * Cbatt * Nbatt;
```

```
                    LPS(t) = El(t)-(Eg(t)+Eb0-(1-
delta)*Cbatt*Nbatt)*eff_inv;
                else
                    LPS(t) = 0;
                end
            end
        end
        LPSP(Npv,Nbatt) = sum(LPS)/El_total;
    end
end
[C,h] = contour(LPSP,60);
clabel(C,h)
colorbar

 PV_cost     = 335.8;
 batt_cost   = 2184;
 slope = - batt_cost/PV_cost;
 x = 1:Nbatt_max;
% % x = 1:Npv_max;
 y = slope * x;
 hold on;
% for k=1:50
% plot(x,y+(k-1)*50,'k')
% end
% %plot(x,y+275,'k')
% ylim([0 Npv_max])

syms x1 y1
for l=1:60
ezplot(y1-slope*(x1-x(l)),[0 50 0 200])
hold on
end
```