MODELING AND SIMULATION OF A COMBINED SYSTEM OF MULTIPLE ROOFTOP PV SYSTEMS AND A CENTRAL ENERGY STORAGE SYSTEM FOR METU ANKARA CAMPUS

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ABSTRACT

MODELING AND SIMULATION OF A COMBINED SYSTEM OF MULTIPLE ROOFTOP PV SYSTEMS AND A CENTRAL ENERGY STORAGE SYSTEM FOR METU ANKARA CAMPUS

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Climate change, increasing energy demand, and natural resource depletion lead to a rapid trend in the adaptation of renewable energy technologies. Especially solar energy as the most abundant source, accompanied by decreasing system prices and increasing social acceptance, rooftop photovoltaic systems became one of the most common small-scale energy generation practices. However, renewable energy resources, solar energy exclusively, create imbalanced energy production throughout the day and year. Energy storage systems are considered to be the solution to this problem. This study aims to investigate the effects of a combined system consisting of distributed rooftop photovoltaic systems and a central energy storage system on the main grid demand. The combined system is considered to be a grid-connected distributed energy system with the purpose of satisfying the energy demand of the Middle East Technical University, Ankara Campus. Modeling of the systems and analysis was run and the results were compared with the usual electricity demand of the campus. Additionally, potential adverse environmental impact reduction created by the systems was also included in the study.

Keywords: Renewable Energy Systems, Rooftop PV, Green Campus

ÖZ

ODTÜ ANKARA KAMPÜSÜ İÇİN ÇOKLU ÇATI ÜSTÜ PV VE ENERJİ DEPOLAMA BİRLEŞİK SİSTEMİNİN MODELLENMESİ VE SİMÜLASYONU

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İklim değişikliği, artan enerji talebi ve doğal kaynakların tükenmesi, yenilenebilir enerji teknolojilerinin adaptasyonunda hızlanmasına sebep olmuştur. Özellikle en bol kaynaklardan biri olan güneş enerjisi, azalan sistem fiyatları ve artan toplumsal kabul ile çatı fotovoltaik sistemleri, en yaygın küçük ölçekli enerji üretim uygulamalarından biri haline gelmiştir. Bununla birlikte, yenilenebilir enerji kaynakları, özellikle de güneş enerjisi, gün ve yıl bazında dengesiz bir enerji üretimi göstermektedir. Bu sorunun çözümü enerji depolama sistemleri olarak kabul edilmektedir. Bu çalışma, dağıtık çatı fotovoltaik sistemleri ve bir merkezi enerji depolama sisteminden oluşan birleşik bir sistemin ana şebeke talebi üzerindeki etkilerini araştırmayı amaçlamıştır. Birleşik sistem, Orta Doğu Teknik Üniversitesi Ankara Kampüsünün enerji talebini karşılamak amacıyla şebekeye bağlı, dağıtık bir enerji sistemi olarak kabul edilmektedir. Sistem modellemesi ve analizler yürütülmüş, sonuçlar kampüsün olağan elektrik talebiyle karşılaştırılmıştır. Ek olarak sistemlerin sağlayacağı olumsuz çevresel etkilerin olası azalımı çalışmaya dahil edilmiştir.

Anahtar Kelimeler: Yenilenebilir Enerji Sistemleri, Çatı-üstü FV, Yeşil Kampüs

To myself for my hard work

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LIST OF ABBREVIATIONS

ABBREVIATIONS

United Nations Development Programme, UNDP

Sustainable Development Goals, SDGs

Intergovernmental Panel on Climate Change, IPCC

Photovoltaic, PV

Distributed Generation, DG

CHAPTER 1

INTRODUCTION

Renewable energy systems have been playing a vital role in climate change mitigation, meeting the increasing energy demand on the global and country-based scale and reducing the ongoing natural resource depletion. Especially, solar energy as being one of the most naturally abundant and free resources has been employed from small-scale for individual use to large-scale solar farms. Rapid implementation of renewable energy technologies has been accepted as one of the main pathways to tackle climate change by various international organizations, and all nations of the world, even becoming one of the main political objectives in many countries. As being one of the leading organizations working on this topic, the United Nation's governing body for international development, the United Nations Development Programme (UNDP), helps countries develop policies, leadership, and partnership skills and increase institutional capacity to achieve the Sustainable Development Goals (SDGs), also called global goals, “which are adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet and ensure peace and prosperity for all by 2030” by UNDP [1]. In achieving Goal 7, named affordable and clean energy, investing in renewable energy is heavily emphasized to be the solution for mitigation of climate change’s adverse effects. The crisis arised in recent years have aggravated the expense of fossil fuel resources used in centralized energy systems. Petrolium products and gas prices are hitting extremes, and the COVID-19 pandemic remains as a hindering force on the restoration efforts while people are worried about whether they’ll be able to afford their energy costs. At the same time, the effects of human-induced climate change manifest themselves in more and more apparent ways. The Intergovernmental Panel on Climate Change (IPCC) warns that between 3.3 and 3.6 billion people already live in highly climate-vulnerable environments [2].

Regarding solar energy, photovoltaics (PV) are expanding in popularity in terms of both research and application. In the year 2021, the world's total electricity generation by solar PV was 994.0 TWh while electricity generation by solar thermal technologies was 18.6 TWh. In the last 10 years, solar PV electricity generation has been multiplied by 15.6 while for solar thermal this number is 6.4 [3]. The electricity generation by solar PV over the world between the years 2000-2021 is given in Figure 1.1. Decreasing solar PV system costs, particularly PV panel prices, well-designed incentives and subsidies aiming to increase the share of renewables in the electricity production market supporting the widespread use of PV on all scales and established public awareness of the benefits of solar energy compared to traditional energy production by fossil fuels enabled this rapid growth in solar PV electricity generation projects. While some incentives focusing on PV systems were adopted more of an inductive method hence concentrating on individual use in some countries, others mainly focused on shifting the national electricity generation away from fossil fuel-based electricity generation technologies, therefore, centering their attention on high-capacity, large scale solar power plants.

Nowadays, the cost of PV electricity generation competes with the cost of power production from other resources and even the retail price, including the rooftop applications. Network electricity prices that include costs of operating the transition and distribution systems, taxes, grid fees, margins, and other charges are usually quite high [4]. The buildings’ electricity demand can be directly supplied by PV systems placed on rooftops, which is categorized as self-consumption. There have been subsidies, premiums, feed-in tariffs and incentives formed to support self-consumption to facilitate the cost of a rooftop PV system to be lower than the grid price hence self-consumption lowers the building's electricity expenses, creating monetary value [5]. Such support policies were in effect for long enough to make it possible that PV system electricity costs can be lower than the grid price even without the subsidies. India, China, and Germany are among many of these examples [6].

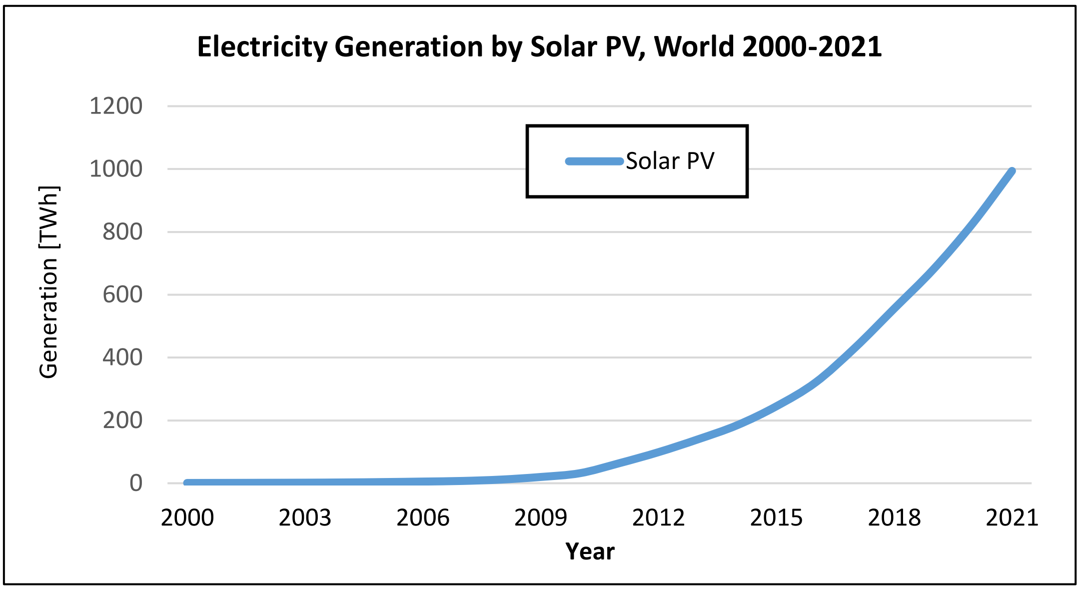


Figure 1.1. Electricity Generation by Solar PV over the World Between the Years 2000-2021

University campuses are quintessential places to encourage the utilization of renewable energy systems. Usually, having a single point of connection to the main grid and having closely located buildings with different electricity demand profiles with various consuming behavior, make campuses miniature grids that include most elements of a large grid such as a city. Also, a significant majority of universities are exempt from certain taxes and legislations on their power consumption and additionally, there are incentives supporting green campus projects aiming to make campuses more sustainable which includes switching to renewable energy sources [7]. The notion of a sustainable university campus was discussed for the first time in the Stockholm Declaration of 1972, which was the starting point of collective efforts for a green future [8]. Therefore, studies on renewable energy systems that are utilized on university campuses are important for the unified goal of sustainability.

Growing renewable energy system applications on the consumer end of distribution lines lead to concerns about managing distributed generation (DG) such as rooftop PV systems for individual or institutional use, as in the case of this study, university campuses. Power usually flows from a higher voltage level to a lower voltage level in one direction even if it can also flow bidirectionally. Therefore, the flow of power is from the transmission network to the distribution network and from there to individual users. Most renewable energy systems installed such as distributed generation systems are designed in a way that allows flow from low voltage to high voltage. However, distributed generation causes problems that the traditional grid cannot handle therefore there is a need for a new, improved and more fault resistant grid system [9]. In order for grid systems to get ready for the upcoming boost of distributed generation by renewable energy systems, studies such as this one are needed.

Taking the intermittent nature of solar energy into account, the use of energy storage has been recognized as a reasonable solution to compensate for the weakness by catering to the supply and demand variability in different time scales (i.e. instantaneous, day-to-day, and seasonal) [10]. Energy storage plays a crucial role in ensuring reliable power supply in a renewable microgrid [11]. Using energy storage systems to smooth the PV power output has been a regularly suggested practice [12]. Therefore, in an attempt to supply the demand of areas with high demand, it is evident that an energy storage system that suits the multiple distributed rooftop PV systems should be used [10-12]. In Figure 1.2 which shows annual energy storage additions between the years of 2015-2020, the increasing popularity for energy storage system is evident [2]. The drop in 2019 is interpreted by IEA reporters as the severe effect of COVID-19, especially in China.

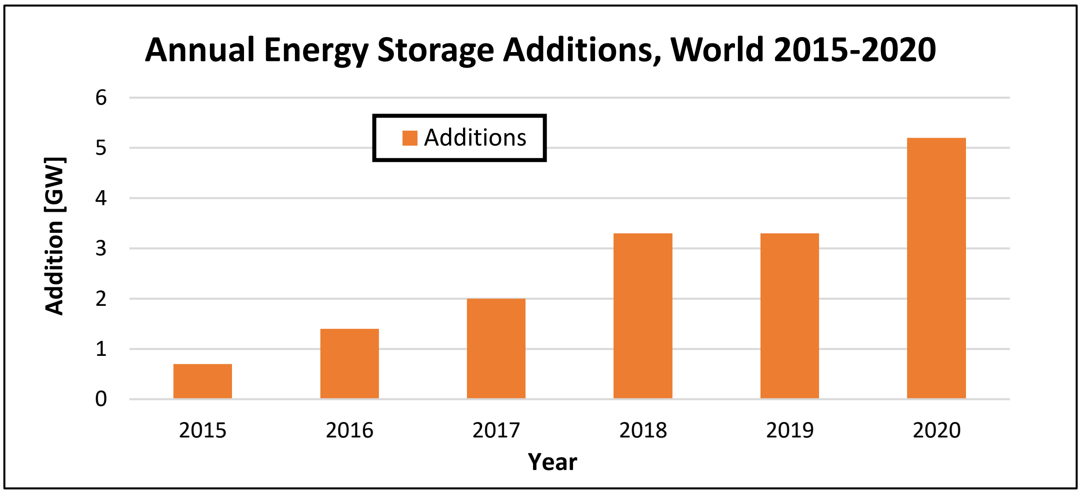


Figure 1.2. Annual Energy Storage Additions over the World Between the Years 2015-2020

In this study, a guideline for modeling and simulation of a combined system that consists of multiple rooftop PV systems and energy storage system (or systems) were developed. This guideline can be applied to model and simulate decentralized or central energy generation systems and if applicable energy storage systems, to any area that has one or multiple types of rooftops. How to interpret the results of simulations and modeling steps are explained in detail. Losses to be considered are also given. It should be noted that this guideline nor this study do not include economical feasibility and detailed environmental impact studies, it is essentially a technical feasibility guideline and study with the addition of avoided CO_2 emission calculations of the total system to give an idea to researchers for the environmental impact potential of the modeled systems.

This methodology has been used to find out the PV rooftop potential and energy storage system potential of the Middle East Technical University Ankara campus. In this case study as a technical feasibility study, rooftop PV systems on multiple suitable rooftops of various-sized campus buildings and a central energy storage system that would help compensate for the intermittency of solar energy were modeled. Simulations were run for a whole year in one-hour time intervals and results were compared to hourly consumption that without the modeled system would be supplied by the main grid hence the Ankara electricity utility. Numerous software were considered for the case study and PVsyst outweighed others in many aspects. The environmental contribution of the modeled distributed renewable energy systems in terms of omited CO2 emissions was investigated as well.

CHAPTER 2

LITERATURE REVIEW

2.1 Studies on Combined Rooftop PV and Energy Storage Systems

In the study conducted by Syed et al. (2020) the energy performance of a three-unit apartment building with a shared energy micro grid that consists of PV panels and a battery energy storage system enabling energy sharing between the apartment units was analyzed [13]. A dataset of one year was assessed in terms of self-sufficiency and yearly average electricity consumption, resulting in a 22% reduction in average yearly consumption and 75% of self-sufficiency. Javeed et al. (2021) studied the optimization of the sizes of two different system configurations, rooftop PV panels only and a hybrid system of rooftop PV and battery energy storage system according to the cost of electricity at four different rates for export and import. Results showed that the optimal capacity for rooftop PV was 9 KWh and for the battery system 6 kWh with the electricity price configuration that uses time of use configuration for export and flat rate for import [14]. In the paper presented by Thanh, T. N. et al. (2021), financial feasibility studies were conducted for two grid-connected systems, one having only rooftop PV panels and the other a hybrid system of rooftop PV panels and battery storage. Results were compared with the experimental data acquired from an office building in Vietnam to examine the real-life performance ratio of the system. The outcome of the study reveals that the system that has only the PV panels was financially more feasible by having 6.2 years shorter rate of return and having 1.9 times the total profits [15].

2.2 Studies on Renewable Energy Systems in University Campuses

The campuses are deemed to be the optimal places to implement sustainable development concepts and employ renewable energy systems [16].

Akindeji et al. (2019), assessed existing university campus micro grids that include different renewable energy generation units and energy storage systems worldwide. Their study shows that campus-wide systems are getting progressively more favorable for both environmental and financial reasons [17]. There are studies that focus on finding the optimal sizing solution for renewable energy resources and energy storage systems, and multiple system configurations with different objective functions are investigated. Khezri et al. (2020) studied a single building in a South Australian campus with an optimization objective of minimizing the net present value of electricity on three modes grid-connected without battery, grid-connected with battery, and standalone hybrid power systems considering rooftop PV, wind power, and a battery storage system [18]. In this study, Shilpa et al. (2019) an optimal grid-connected PV system configuration for the Sri Jayachamarajendra Polytechnic campus in Bangalore was designed and compared with an off-grid PV-diesel generator hybrid system. Simulations were conducted using the software HOMER [19].

Studies that focused on rooftop PV applications on campuses or educational institutes such as the study conducted by Khan et al. (2021) which proposes an off-grid rooftop PV system for the academic building of Jashore University of Science and Technology, a university campus in Bangladesh are available in literature [20]. The proposed rooftop PV and battery storage hybrid system aims to meet the demand of the fan and light loads for one building and evaluation shows sufficient economic feasibility for the country. Mokhtara et al. (2021) suggests a design approach combining techno-economical optimization and spatial analysis for a grid-connected rooftop PV system. The design approach is focused on educational building in arid environments and for the study, a university campus in Algeria has been chosen. A multi-objective optimization approach was adopted and software Ecotect, ArcGIS, and HOMER have been used. Results show that 60% of the rooftop area was suitable for rooftop PV application with 17 degrees of inclination. Analysis indicates that the suggested system is highly self-sufficient and even able to reach grid parity [21]. Baitule et al. (2017) conducted a feasibility analysis for the proposed PV systems on the free land area and rooftops using both PVsyst and Solar Advisory Model software on the campus of Maulana Azad National Institute of Technology, India. Results reveal that proposed distributed systems that has a performance ratio of 0.74 with 73 318.0 tons of carbon footprint reduction annually [22]. Sharma et al. (2018) worked on a technical analysis involving the simulation of the PV system to achieve maximum power under different load conditions in a single building using PVsyst software. Along with the calculation of efficiency and performance ratio, the feasibility analysis of the system in terms of CO2 emission was also conducted [23]. Performance ratio of the final design is 81.0%.

In the study conducted by Barua et al. (2017), the aim is to design and run a feasibility analysis of the performance of a grid-connected PV rooftop system for Pondicherry University campus using PVsyst and studying the considered project area by using the NASA surface meteorology data. The analysis reveals that 590MWh of annual energy was produced by the system which is about 11% of the total annual energy consumption on the campus [24]. Krishna et al. (2021) studied the design and the economic analysis of three rooftop PV systems using PVsyst software and the economic study was conducted to determine the design’s operative efficiency which resulted in an impressive 8-year payback period [25]. The aim of the study ran by Thaib R. (2019) is to run an economical and technical feasibility study on multiple rooftop PV systems for the campus of the University of Samudra within the scope of the university’s development plan. Results of the feasibility analysis conducted using the System Advisor Model (SAM) software showed that the system has a 15.4-year payback period and covers a significant amount of the daytime demand of the campus [26].

2.3 Studies on Combined Rooftop PV and Energy Storage Systems in Turkey

There are several studies conducted that include the technical and/or economical analysis of rooftop PV systems within Turkey. Some of these studies focused on single buildings, aiming to meet the demand of the studied buildings, whereas some were analyzing the potential of an area such as a city or a province, and some were conducted to analyze the economical and electrical aspects of the systems on a larger scale.

The paper presented by Akpolat et al. (2019) is about the design and simulation of a rooftop PV system on the roof of the faculty building of Marmara University, İstanbul. For the analysis, PVSOL software has been used and results show that the 85 kWp grid-connected system can meet 13.2% of the building's annual electricity consumption [27]. Inan (2019) designed and conducted a technical and economical feasibility analysis of a rooftop PV system for four blocks of a public building and its parking lot in Istanbul using PVSOL software. The designed system meets 26.8% of the annual electricity demand of the building with a remarkable payback time of 5.3 years [28]. In the study by Homood et al. (2020), the Building Information Modeling tool has been used to choose the suitable regions with high solar radiation to further investigate the potential electricity production of a rooftop PV system for a single-family house. Both PVsyst and PVSOL software were used to conduct analysis and the difference in energy output, performance ratio, and energy yield values between two software results are deemed to be due to difference in weather database software use. However, it is concluded that these software simulations were close to each other [29].

2.4 Key Contributions of The Study

Table 2.1 Summary of Literature Review

Ref.	Rooftop PV	Energy Storage	Single Building	Multiple Users	Campus	Place	Results
[13]	✓	✓	✓	✓	×	Perth, West Australia	**75% self-sufficiency** for three-unit apartment
[14]	✓	✓	✓	×	×	South Australia	Comparison study of PV system vs. PV+battery, **lower LCOE** for hybrid system
[15]	✓	✓	✓	×	×	Vietnam	Comparison study of PV system vs. PV+battery, PV sys. **econ. feasible**
[17]	✓	✓	×	✓	✓	-	**Assesment** of existing campuses in terms of renewable energy generation and energy storage
[18]	✓	✓	✓	×	✓	South Australia	Comparison study of PV vs. WT vs. hybrids, best is **PV+WT+storage**
[19]	✓	✓	×	✓	✓	Bangolore, India	Comparison study using **HOMER**, grid-connected PV vs. off-grid PV+diesel generator resulting in **better PR** of grid-connected PV
[20]	✓	✓	✓	×	✓	Bangladesh	PV+battery has **sufficient ecnonomic feasibility** for the country
[21]	✓	✓	✓	×	✓	Algeria	**60% of rooftop** is suitable, hybrid system is **highly self-sufficient**.
[22]	✓	×	×	✓	✓	India	**0.74** PR, **73,318** tCO2 GHG reduction emission
[23]	×	×	✓	×	✓	India	Technical analysisusing **PVSyst** software, **0.81** PR
[24]	×	×	×	✓	✓	Pondicherry, India	Feasibility analysis of grid-connected PV systems achieving **11% of annual consumption**
[25]	✓	×	✓	×	✓	Malaysia	Design and economical analysis using **PVSyst**, concluded in **8-year payback period**
[26]	✓	×	×	✓	✓	Indonesia	Economical and technical feasiblity analysis for multiple rooftops, **15.4-year payback period**
[27]	✓	×	✓	×	✓	İstanbul, Turkey	Design and simulations for a rooftop system using **PVSOL**, **13.2% of demand** is met
[28]	✓	×	×	×	×	İstanbul, Turkey	Technical and economical feasibility analysis using **PVSOL**, **26.8% of demand** is met, **5.3-year payback period**
[29]	✓	×	✓	×	×	Elazığ, Turkey	Grid-connected system simulation on both **PVSyst** and **PVSOL** has been used the difference between PR is **3%.**

In Table 2.1, a summary of literature review including the significant results of the studies is given.

This study provides a guideline to calculate the potential of available rooftop area for rooftop PV applications for an area with multiple buildings regardless of the type of rooftops, the potential energy output from the distributed rooftop PV systems, the potential excess energy created by these rooftop PV systems that can be stored in energy storage systems, the consumption of the area that potentially can be met by the energy supplied by the combination of the distributed rooftop PV systems and central or distributed energy storage systems. The presented guideline includes a methodology for detailed data acquisition on suitable rooftop area, weather data to be used for calculations and consumption data of the area, providing methods to evaluate the acquired data, suggests suitable software and ways to interpret the results and a calculation method for avoided CO_2 emissions to provide some insight on the positive environmental impact of the designed systems. Study presents this guideline's application on METU Ankara campus as an extensive example case study.

There is not such a study in the literature that combines all of the mentioned aspects of the guideline and an application of suggested methods to acquire these results altogether for an area with multiple buildings. The following two points are given as secondary contributions that can be extracted from the results of the study:

- Many developing countries are still struggling to meet their electricity demand and tackling the challenge of transitioning the grid to accommodate better to renewable energy generation especially in distributed generation form. Therefore, building grid infrastructure and increasing the capacity of power plants, expanding the reach of transmission and distribution lines are vital for the future [30]. While implementing new renewable energy technologies into existing power systems, designing the optimal system and configuration is essential. Therefore, to maximize the benefits of several power generation options for both suppliers and end-users, the system operation's safety and functionality of the system has to be maintained.

- The intermittent renewable power generation introduces unique challenges such as non-traditional energy generation scheduling and significant impact on electricity supply from utilities on local markets [31]. Several lobbying campaigns against decentralized solar energy have been carried out in accordance with the common belief that decentralized generation would be against the utility’s interest because DG reduces the size of the utility's market by promoting self-consumption, and policies require the utility to purchase excess generation from customers at a higher price than they sell [32]. When developing energy legislation and policies, it is necessary to evaluate how utilities would interpret and implement regulations to safeguard their own benefits instead of consumers and society [33]. Alternative policies and strategies are needed to help enhancing rather than limiting the use of renewable energy resources. Thus, studies such as this one are needed to inform policy makers on the technological, environmental and economic benefits and outcomes of combined rooftop PV and energy storage systems that will become progressively more wide-spread so that flexible strategies could be developed for both utilities’ and consumers’ benefit

CHAPTER 3

METHODOLOGY

In this chapter, the guidline or series of methods that are designed to calculate the afromentioned potentials are presented. First, the data that would be needed to conduct such study are given., Second the method to be followed while choosing the studied area is given. In the third part of this chapter, points to track for the selection of software to be used for modeling and simulations are given. Methods for rooftop PV Systems' and energy storage systems' modeling are given in forth and fifth parts of this chapter respectively. The method followed for the interpretation of the results is given in the last part of this chapter.

It should be noted that while studying the data acqusition part, checking whether the needed data are available for the considered area that is wished to be studied using the presented guideline is crucial for the next steps.

3.1 Selecting the Area to be Studied

There are certain things that should be considered while deciding on the area to be studied using this guideline. First is the availability of required data in the correct format. If the data of the considered area is not accessible due to lack of measuring and generating the required data through other databases is not possible, then another area must be considered.

It is important that the area to be studies is suitable for rooftop PV applications. In Figure 3.1, the long-term daily and yearly total averages of global horizontal irradiation given by Global Solar Atlas is presented [34]. This map is useful in giving a general idea of the total global horizontal irradiation that reaches an area. If the considered area has low irradiance for the expected consumption, another area should be considered.

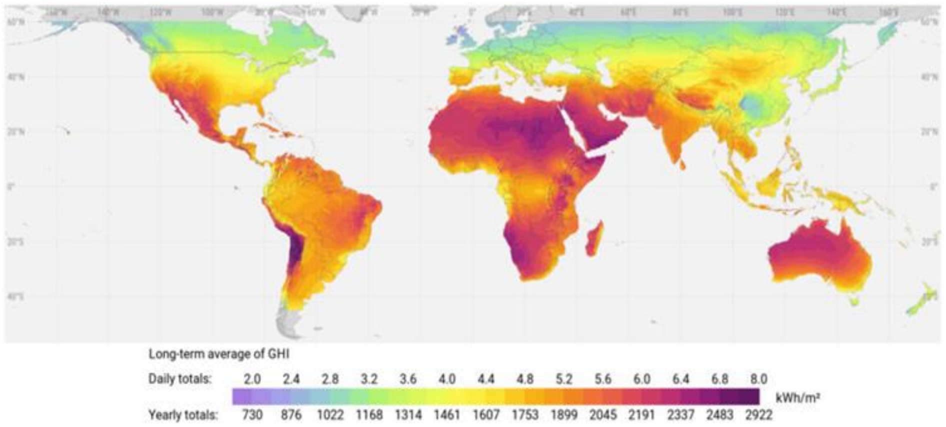


Figure 3.1. Long-Term Yearly Average of Daily and Yearly Totals of Global Horizontal Irradiation

Another matter to pay attention is the rooftop types of the area. Pitch angle of the roofs that is allowed by the governmental organizations and institutions in the considered area and legislations around this is important. Also, if the configurations of building roof shapes are complicated (e.g., having sides with different pitch angles or dormers).

3.2 Required Data

The main data to be acquired to follow the modeling and simulation methods presented in this study are weather data, data of the area’s electricity consumption and available rooftop area. Since all of the simulation are conducted in time intervals of one hour for a year, all of the required data that change depending on time should be acquired in one-hour intervals or less (e.g., 15-minute time intervals). Additionally, the data on energy mix and CO_2 per unit of total primary energy supply of the chosen area should be acquired for the avoided CO_2 emission calculations that will be conducted after results are obtained.

3.2.1 Meteorological Data

Meteorological data are essential for calculation of how much energy output PV panels would supply. The solar irradiance values, ambient temperature, wind velocity, relative humidity, dry bulb temperature, dew point temperature and clearness index are some of the most important values that effects the output of simulations. Solar irradiance data covers global horizontal irradiation, diffuse horizontal irradiation, horizontal beam irradiation and normal beam irradiation. Irradiance data is the most important data for all solar PV simulations since these are the starting point of all simulations combined with clearness index. Ambient temperature effects the efficiency of the PV panels and rest of the system components. Wind velocity, relative humidity, dry bulb and dew point temperatures also effects the simulation results in different aspects and there are experimental studies on these effects and studies on how to model these affects in different climates [35-39].

Depending on the theoretical model and assumptions that are going to be used for the simulations, the weather data that will be used in the calculations change. However, the most important data stays the same as irradiation and ambient temperature. There are several weather data formats and databases that are commonly used in academic literature and non-academic field work. Most popular ones for solar irradiation data are TMY2 and TMY3 that are usually used for building simulations, meteo data from Meteonorm software that is used by Solar PV design and simulation software such as PVsyst and Helioscope, NASA-SSE, NREL's National Solar Radiation Database (NSRD), Solargis data that can be in time series or TMY formats, PVGIS meteorological data that is used in PVGIS software for simulations etc. Wind atlases can be used for wind velocity data if not available within the datasets that includes solar irradiance data. Some of these datasets are location based such as USA or Europe. Therefore, it is important to check whether the data of the studied area is available in the desired time interval which is hourly in this study. It is also possible to generate synthetic data for locations that the hourly meteorological data is not readily available. For instance, Helioscope software uses Meteonorm software to stochastically generate hourly values from monthly irradiance values [40].

Therefore, it is important to take into consideration that the location of the area where this guideline is going to be followed, whether there is data available close to the to-be chosen simulation site, which design and simulation software might be used and which type of database or data format that the software accepts while choosing a database or/and data format. Also, some data formats do not include all the weather data, or some software do not use some weather data such as Solargis including Aerosol Optical Depth or Precipitable water data while PVsyst software not benefiting from it [41].

3.2.2 Electricity Consumption Data

The electricity consumption data of the chosen area is needed so that the percentage that would be potentially met by the designed system could be calculated. Additionally, it is important to understand and evaluate the consumption behavior of the area so that the most suitable energy storage system could be designed. It is also possible that the potential electricity output of the rooftop PV systems might be more than the consumption. Therefore, this data is needed not just for the results but also the designing stages. Data should be in at least one-hour intervals and in the same unit that the simulation results will be or else should be converted to desired form.

The consumption data should be evaluated in terms of monthly total consumption to evaluate the seasonality of the consumption, hourly averages to evaluate the change in consumption from day to night. Further analysis can be conducted on consumption data according to potential system needs.

If the consumption data of each individual building is available, then the simulations will be richer. If it is not available, then the building of the area will be considered as one entity while the rooftop PV systems will be modeled as distributed generation units. As an alternative there are tools to model individual use of each building if certain data is available, such as the user behavior information (e.g., residential or commercial electricity user) or information on the appliances in the building.

3.2.3 Available Rooftop Area

Data on rooftop area might be readily available for some areas in the form of building plans. Some statistical institutions (governmental or private) collect and keep the rooftop area data. If this information is available, after acquiring the data, it is possible to use several methods to derive the available rooftop area from the acquired data. If data on available rooftop area is not readily available, satellite mapping software or websites such as Google Earth, Google Maps, Bing Maps etc. could be used with the built-in distance or area tool. The quality of the satellite imagery is important in this aspect. However, high resolution images of especially the urban regions are usually available free online.

Some solar simulation software employ built-in tools to calculate available rooftop area, considering and calculating the available area by excluding the effects of the shadowing elements that might make PV application impossible or inefficient. These shadowing elements can be near shadings such as other buildings or trees shadowing the to-be studied rooftop, AC units and chimneys on the rooftop itself or far shadings such as mountains or hills. For instance, Helioscope software has a built-in tool that simulates the shading area that would be created by an on-rooftop near shading element and calculates the shadow free area of the rooftop hence the available rooftop area. For other shading elements, there are 3D scene building tools where the building of the rooftop and near shadowing elements can be modeled around it. This tool simulates and calculates the shadows of other elements on the rooftop and the loss due to shadows, giving user the necessary information to determine the available rooftop area. For far shadings, software present intricate horizon-line calculations.

In order to calculate the available rooftop area, one can employ one or a few of these methods and compare the results to react the most realistic conclusion.

3.3 Software Selection

There are numerous software tools available for commercial or academic use that are designed to be used for modeling and simulation of renewable energy systems. Some of these software have a focus on PV systems such as PVsyst, PVSOL, PVGIS and Helioscope, some are focused on the combined system design that includes distributed generation by multiple renewable energy sources such as HOMER Grid [42-44]. It is also possible to use mathematical modeling tools such as MATLAB Simulink.

Milosavljević et al. (2022) had a comparison study among simulation and software tools that are frequently used in solar PV system design and simulation. Results suggest that PVsyst is one of the most efficient software with several system component settings and the ability to conduct and compare multiple evaluations [45]. Also, the study conducted by Özden et al. (2020) indicated that while the performance of compared software was acceptable, the best performing one was Helioscope and the next best one was PVsyst [46].

3.3.1 Selecting the System Components

Each system component should be selected before the modeling and simulation stages according to the system needs. Choices might be limited by the country’s legislations or government policies where the area that is selected to be studied. For instance, in many countries incentives encourage sourcing components of PV systems locally or it is made obligatory [47-48]. The steps to follow while selecting the system components are selecting the PV panel and then selecting the optimizers and inverters.

3.3.2 Optimizing the Panel Orientations

As a rule of thumb, if the latitude angle of the area where the PV panels are going to be used is between 25° to 50°, the optimum tilt angle is the result of latitude angle multiplied by 0.87 and 3.1 degrees added. Another rule of thumb suggests that the optimum tilt angle is calculated by adding 15 degrees to the latitude of the studied area during winter and subtracting 15 degrees from the latitude during summer.

Furthermore, most of the solar PV simulation software have tilt and azimuth angle (or panel orientation) optimizers that gives the optimal panel orientation for the optimization goal. This goal might be achieving the highest energy output during summer, winter or throughout the whole year.

The optimization of both tilt and azimuth angles have to be conducted for all of the buildings that will be used in modeling and simulation according to the optimization goal. Because the orientation of the building itself, the dimensions and the shape of the building affects the possible placement of the PV panels hence the maximum energy output of any panel orientation.

3.4 Designing the Rooftop PV Systems

The rooftop PV systems should be designed according to the electricity consumption needs of the studied area. If the goal of the system design is for area to be as self-sustaining as possible then the systems have to be designed for maximum self-consumption. Besides self-consumption, system goals might be peak shaving, complete or partial islanding etc. Therefore, it is important to understand the needs of the users in other words the consumption scheme of the buildings. For a self-sustaining system the rooftop PV systems should be designed in a way where there is excess electricity production to store and supply to buildings when demand cannot be met by just the production from PV system.

Country policies and economical limitation can be considered if the goal is to evaluate the systems in those aspects. However, this guideline does not take these aspects into consideration in the designing stages since this study is just a technical feasibility study.

Losses to be considered while designing the system are incidence losses, near shading losses, PV losses due to irradiance level and temperature, array mismatch losses, light-induced degradation loss, wiring losses, soiling loss, system unavailability loss and inverter losses.

Most solar PV simulators have optimizers that optimize the placement of the panels to reach the maximum electricity output for given geometry and dimensions of an area. Employing these optimizers together with panel orientation optimizers would be the easiest and the fastest way to determine the characteristics of the final rooftop PV system design.

3.5 Designing the Energy Storage Systems

Energy storage systems have been used to compensate the intermittent nature of renewable energy resources such as wind and solar. If the renewable energy systems are designed to meet the demand of the area that the system supplies electricity as much as possible with an electricity user profile that is constant or that has night consumption, the energy storage systems have to be considered.

There are different energy storage system technologies that might be suitable to be paired with renewable resources depending on the location and limitations of the systems. There are battery storage systems such as lead-acid and lithium-ion technologies, systems that use thermal storage, pumped hydro, compressed air, flywheel energy storage, fuel cells, superconducting magnetic storage and super-capacitors [49]. All these energy storage systems have its own advantages and disadvantages that changes according to the capacity of the energy producing unit, location, weather conditions and the configuration of the electricity system.

It is common practice to use Lithium-Ion energy storage technologies with different renewable energy resources since 2018. In Figure 3.2, it is shown on the study conducted by Hernandez Martinez et al. (2020) that the production of lithium-ion batteries has been increasing while the cost of solar PV modules were decreasing therefore the use of Lithium-ion battery technology applications were increasing with the increase of PV use [50].

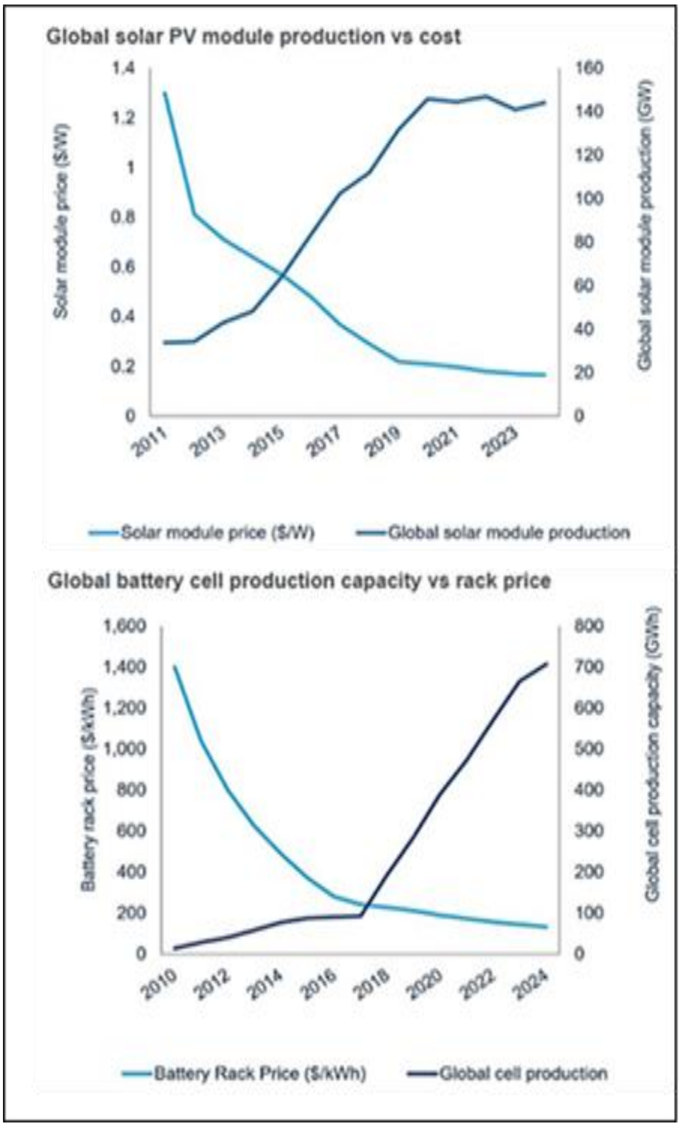


Figure 3.2. Solar PV and Lithium-ion Economies of Scale Comparison

Considering the economical implications, geographical limitations, the state-of-art of the technologies and the concerns on the areal application, the battery storage systems are the most suitable for the models that are going to be designed for the systems that have PV systems as the power generation unit. Lithium-ion battery technologies were preferred over lead-acid battery technologies for several reasons in the study done by Kebede A.A. et. al shows [51]. First is that lithium-ion batteries have a longer lifetime compared to lead-acid ones. Secondly, lithium-ion batteries require 40% less number of batteries compared to lead-acid batteries, hence less space. Thirdly lithium-ion batteries have a lower cost of energy compared.

According to the results obtained from the simulations of modeled multiple rooftop PV systems the potential for an energy storage system can be calculated. If the modeled PV systems do not produce any or very little excess electricity output, then there is no need for a storage system and according to the legislations of the country, excess can be sold back to the grid. If there is enough excess electricity output, energy storage systems can be considered according to the needs and limitation of the system. And if the excess electricity is a lot more than the demand then energy storage systems should definitely be considered as an essential part of the energy systems of the studied area, if technically feasible. For systems that produces rather low excess electricity in terms of time-availability (the time that passes between the excess electricity supply and high demand that cannot be met by the PV is short) battery storages are a better option. For systems with high excess electricity production in time-availability terms energy storage systems such as pump hydro or thermal storage, if feasible.

The energy storage system can be designed as distributed or central depending on the acquired consumption data. In other words, if the consumption data of each building is present then an energy storage system for each rooftop PV system can be modeled. The storage strategy can be different depending on the system needs. Among several storage strategies the most applied ones are the aforementioned strategies which are, self-consumption, peak-shaving and weak (partial) islanding. Losses that should be considered changes for each energy storage system. For battery storage systems, which has a higher probability to be the chosen system if this guide is used, charging and discharging voltages and currents, battery temperature and aging are the important parameters. Losses that must be considered are operating losses for battery charger and for discharging inverter, the battery energy loss that can occur due to internal resistance, high current issues due to overcharging and charging-discharging efficiency losses.

3.6 Interpretation of the Results

The suggested results that should be interpreted and evaluated after conducting the simulations are:

- Total and individual rooftop PV system electricity outputs, in hourly, daily, monthly and yearly terms (and seasonal if deemed necessary)
- Comparison of rooftop PV system outputs with the consumption data in hourly, daily, monthly and yearly terms to understand whether energy storage systems are needed and to recognize how much of the hourly demand or total consumption that these system outputs can meet
- PV system efficiency which is energy output divided by available solar energy
- Performance ratio which is the ratio of the system output to theoretically possible output
- Renewable energy fraction which is the energy provided by the system divided by the total energy demanded by the system hence the consumption
- Percentage of the consumption met during the day or sun hours which is the hours where the sun is up hence the PV production is possible to determine how much of the user’s needs are met by the rooftop PV systems
- Total energy loss in hourly, daily, monthly and yearly terms
- Total and individual combined system outputs, in hourly, daily, monthly and yearly terms

- Comparison of combined system outputs with the consumption data in hourly, daily, monthly and yearly terms hence percentage of consumption met
- Combined system efficiency

This list can be extended according to design goals and system configurations. For instance, it is important to check the battery charging and discharging durations to verify that the battery systems are working within the design goals.

After the results are acquired, avoided CO_2 emission by the systems can be calculated using the tonnes of CO_2 per unit of total primary energy supply in tCO_2/TJ calculated for each country according to country's energy mix.

CHAPTER 4

MODELING AND SIMULATIONS OF SYSTEMS FOR METU ANKARA CAMPUS

In this chapter of the study, the modeling and simulations conducted by following the methodology presented in the chapter three are given.

4.1 Studied Area: METU Ankara Campus

Middle East Technical University was founded on November 15, 1956, enclosing a campus area of 4500 hectares with a forest area of 3043 hectares, including Lake Eymir. Starting its first academic program in 1956, METU now has 5 faculties with 41 undergraduate programs and 176 graduate programs [52]. METU has more than 150 buildings for educational purposes including classrooms and labs, more than 100 for residential purposes including dorms and housing for university staff, and several administrative and commercial buildings. Therefore, there are several buildings from different categories of electricity demand and with different roof sizes.

Required information and data such as hourly electricity demand and grid configuration were readily available within the METU campus. Such information is hard to acquire because of the intricate bureaucracy between Turkish utility companies and governmental institutions. Therefore, METU Ankara Campus was chosen area for this study.

4.2 Data Acquisition

4.2.1 Meteorological Data for METU Ankara Campus

For this study, the meteorological data from Meteonorm 8.0 database has been used. The acquired data from the database was compared with the data acquired from the Turkish General Directorate of Meteorology. The comparison results show that the dataset of Meteonorm 8.0 shows 92.3% similarity with the data acquired from the Meteorology Directorate however the data from the Meteorological Directorate is in daily format, thus the daily averages of hourly data acquired from Meteonorm 8.0 were taken for the comparison. Therefore, even if the similarity percentage is promising, it should be kept in mind that it is not possible to verify the Meteonorm 8.0's meteorological data unless there is a meteorological data collection unit in the studied area.

The hourly meteorological data acquired from Meteonorm 8.0 database includes global horizontal irradiation, horizontal diffuse irrediation, horizontal beam radiation, normal beam radiation, cleaness index, ambient temperature, wind velocity and relative humidity. This data is synthetically generated from monthly meteorological data hence does not belong to one particular year. The data acquired from the Meteorology Directorate only contains daily average temperature and daily sun hours from the year 2020 which is the year when the hourly consumption data of the chosen area was available.

4.2.2 Electricity Consumption Data of METU Ankara Campus

The electricity consumption of the campus was acquired from the METU Directorate of Electricity Management for the year 2020, in fifteen-minute intervals. Then, this data was converted to the hourly electricity demand of the campus. In Figure 4.1, graph of monthly electricity demand of the campus is presented. Total yearly demand is 26829 MW. In Figure 3.2, graph of hourly averages of electricity demand of the campus is shown. This graph clarifies that campus has an average base electricity demand of 2551 kW hourly.

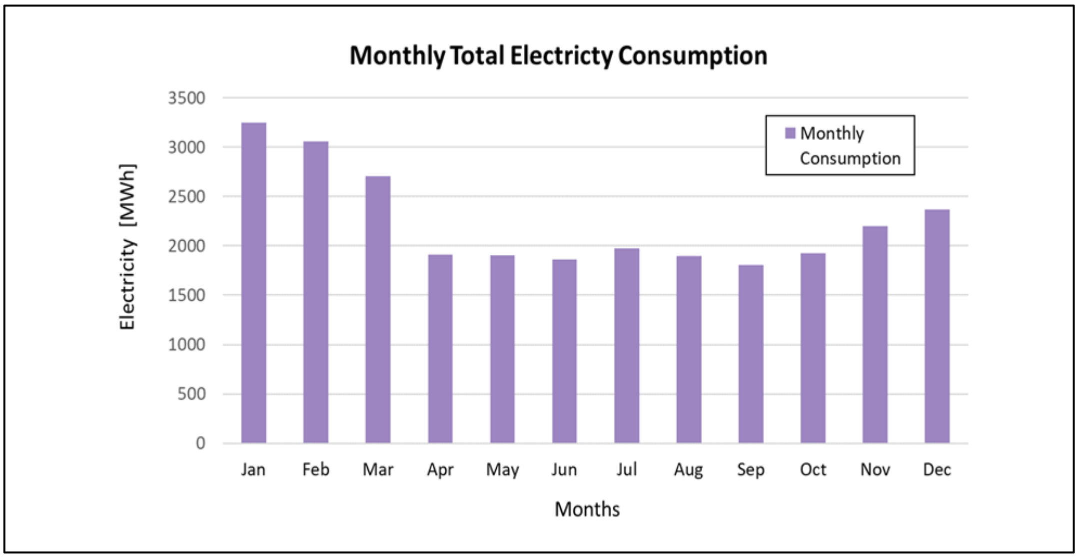


Figure 4.1. Monthly Total Electricity Demand of the Campus

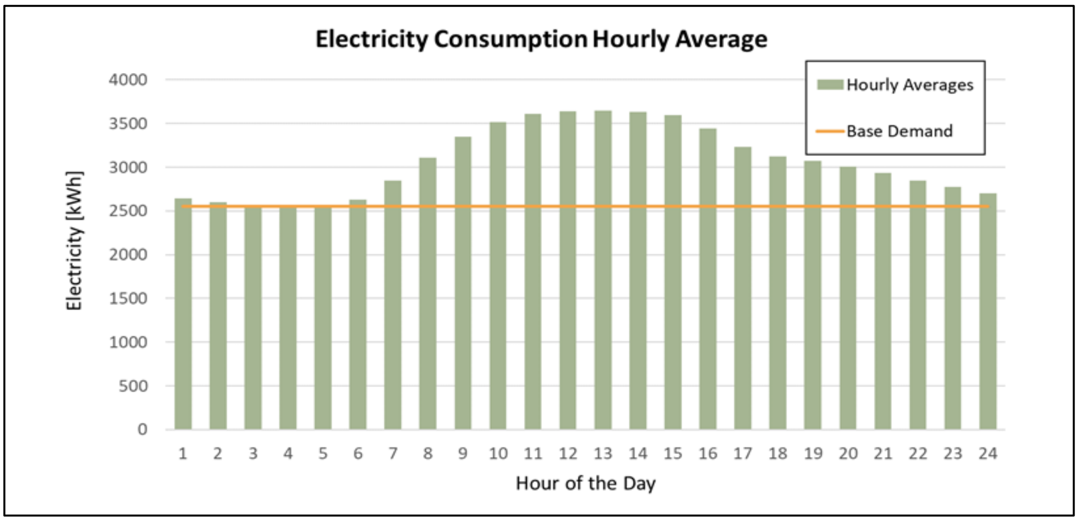


Figure 4.2. Hourly Averages of Yearly Electricity Consumption

The average demand rises during the day and stays around the base demand during the night. In Figure 4.3, it is shown that hourly averages of demand for each month follows a similar profile. It should be noted that, the consumption (or demand) data belongs to the year 2020 where the Covid-19 restrictions started at the middle of March and lasted till the beginning of September 2021. Acquiring the consumption data of previous years was not possible since the hourly consumption data that belongs to previous years gets deleted from the system every month. For instance, hourly (or 15-minute intervals) data of March 2019 gets deleted at the end of March 2020. Therefore, it was not possible to acquire consumption data that included a full year that covid-19 restrictions were lifted. However, monthly consumption data of 2019 was available. Comparing the monthly total consumption of 2020 and 2019 suggests that the overall profiles are similar but the sharp decrease in April is less extreme.

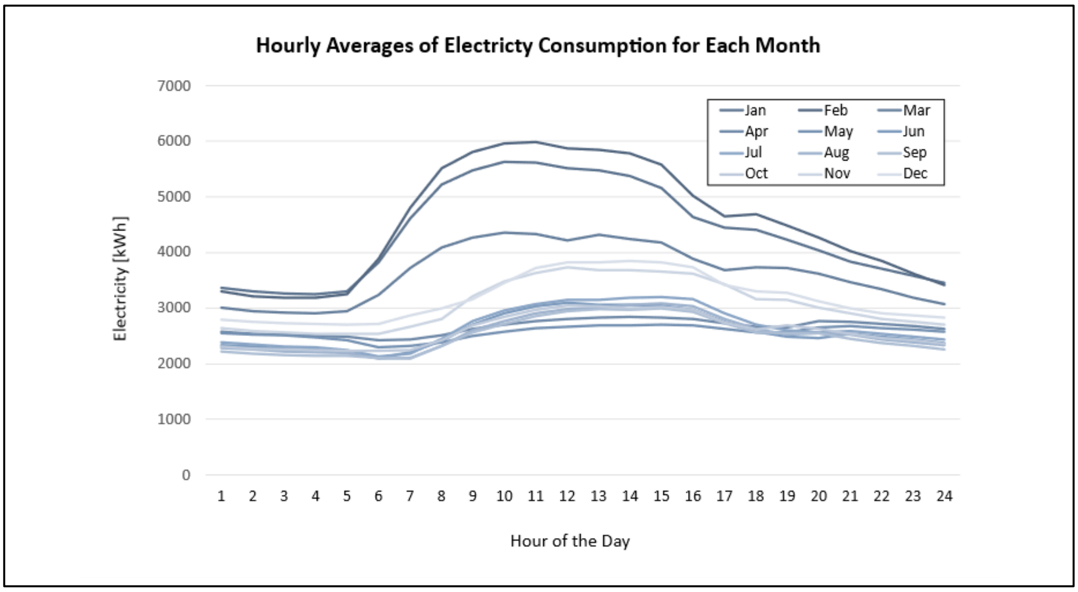


Figure 4.3. Hourly Averages of Electricity Consumption for Each Month

It should be noted that acquiring the individual consumption data of each building of the campus is not possible since there is no individual metering in the campus besides the residential buildings. Modeling the consumption scheme of each building requires a great length of field research.

4.2.3 Available Rooftop Area of METU Ankara Campus

Data on rooftop area was calculated with the help of AutoCAD computer aided design software since the data on rooftop area was not readily available as building plans or in the form of statistics. AutoCAD enables the user to handle high resolution satellite imagery acquired from Bing Maps or Google Maps and make distance measurements to get the area of rooftops. This method has been used to calculate the suitable rooftops of buildings keeping shadowing elements such as trees, AC units located on rooftops, other closely located buildings and chimneys in mind. Some buildings in the campus were not suitable for a rooftop PV application due to shadowing elements around the roof, mainly trees. Helioscope software has a reliable feature called shade modeling where software calculates the shading area of any obstacle, mentioned as shading elements in this study, and shows the suitable rooftop area. In order to verify the results obtained using AutoCAD, Helioscope's shade modeling has been used for selected buildings. Results show that calculations made with the help of AutoCAD were more on the conservative side with an average error of 9.7%. As another way of verification, Google Earth's distance measurement tool has been used. Results were closer to the AutoCAD calculations. It should be noted that the biggest difference between the calculations of AutoCAD and Helioscope were on the rooftops with chimneys where Helioscope, a software made in USA, has to make assumptions that are more applicable to USA. For instance, in Turkey, it is required that chimneys are made according to DIN 4705 standards, however in US standards that must be followed are NFPA 211 where for DIN 4705 calculations are made according to pressure of smoke and for NFPA these are done according to height measurements [53-54]. Thus, it is safe to assume that Helioscope might use assumptions applicable to USA and that are not applicable for Ankara, Turkey. Therefore, to be used in this study choosing the calculations made on AutoCAD was a safer option.

The table of each suitable building and the area has been given in Appendix A. 64 building rooftops were deemed to be suitable for modeling.

PVsyst software has a feature where the horizon line can be drawn and the losses due to far shading (such as mountains) can be calculated. However, using this feature was not possible for this study since it wasn’t possible to draw an accurate horizon line for each building without intensive measurements taken for each building. Near shading elements were considered while calculating the suitable rooftop area for each building.

4.3 Software Selection for the METU Ankara Campus Study

For this study, software that can simulate PV systems that are combined with energy storage systems was needed. Helioscope does not offer that feature but, PVsyst has a quite adequate feature that helps the user model and simulate islanded or grid-connected hybrid PV power generation and energy storage systems. Therefore, PVsyst was the chosen software for the ease of use, its capacity of linking modeled systems, detailed options for grid-connected systems that include batteries, also there are resources such as help guides available online.

4.3.1 Selection of System Components

4.3.1.1 Selection of PV Panels

PVsyst offers a series of generic PV panels and inverters for users with detailed spec sheets to design systems that do not have financial or material requirements [42]. The characteristics of these panels and inverters are realistic averages of commonly used equipment. Since this study does not have financial requirements, there is not a list of PV panels to choose from or inverters for this study, unlike a real-life project which would have such limitations. LONGi Solar, Tongwei Solar, Jinkosolar, Aiko Solar and Hanwha Q Cells are the PV panel manufacturers that have the highest shipment capacity in gigawatts available [55]. The PV panels with the highest Nominal Power that are in PVsyst’s own database have 590 Wp nominal power. This panel is manufactured by Hanwha Q Cells. The spec sheet of the panel has been presented in the Appendix B. Therefore, the 590 Wp Hanwha Q Cells panels have been used to design the systems throughout the modeling stage.

4.3.1.2 Selection of Optimizers and Inverters

PVsyst offers an extensive library of inverters as well as panel integrated power optimizers that are up to date until the year of 2021. After choosing the PV panels and indicating the available module are at the system section of PVsyst, the next step was choosing the optimizer and then the inverters. Power optimizers are essentially direct current (DC) to DC converters that are placed at the back of PV panels or wind turbines to maximize the power that can be harvested from the power production unit using maximum power point tracking (MPPT) by tracking the maximum power produced by each unit in real time and converting the voltage and current to an optimal value so that the inverter receives electricity at a voltage that would result in the maximum power output. Power optimizers can smooth out the losses that might be created by partial shading on PV panels in a string. Since the maximum power output of a string of PV panels is limited by the performance of the PV panel that produces the least power, even being slightly shadowed can increase the resistance of a PV panel and lower the power output. Hence power optimizers are used in PV panel applications [56]. However, one disadvantage of power optimizers is that certain optimizers work only with certain PV panels and inverters. Therefore, for the modeling stage of this study, power optimizers that can work with the chosen PV panel have been used. Chosen power optimizers for this study change for each system however, some SolarEdge power optimizers are always compatible with the chosen PV panel hence all the power optimizers used for modeling are from SolarEdge and the list of power optimizers used for each building can be found in Appendix B.

The inverters that are available in the PVsyst database that are compatible with the SolarEdge power optimizers are only SolarEdge Inverters. The list of inverters that have been used for each building in this study can be found in the Appendix B.

4.4 Designing the Systems for METU Ankara Campus

4.4.1 Designing the Rooftop PV Systems for METU Ankara Campus

4.4.1.1 PV Panel Orientation Optimization

For METU Campus the calculation of the first rule of thumb would result in 37° of tilt angle, while the second rule of thumb would result in 49°for winter and 19° for summer.

PVsyst offers a quick optimization scheme for optimal plane tilt and orientation. Tilt angle of 35° is the tilt angle that gives the optimal results with respect to yearly irradiation yield with the azimuth angle of 0° as shown in Figure 4.4. Software also provides quick optimization results for summer irradiance yield and winter irradiance yield, assuming summer as the time frame between April to September and winter as October to March. The optimization results for these time frames are shown in Figure 4.5 and Figure 4.6 respectively. “Plane orientation” given in the figures is the azimuth angle of the plane and “Loss/opt.” is loss with respect to optimum. PVsyst takes optimum as the highest energy yield for the given time frame. With azimuth angle of 0° quick optimization gives zero loss for yearly irradiation yield for 35° of tilt angle, for summer irradiation yield the optimum tilt angle is 20.5° and for winter 55°.

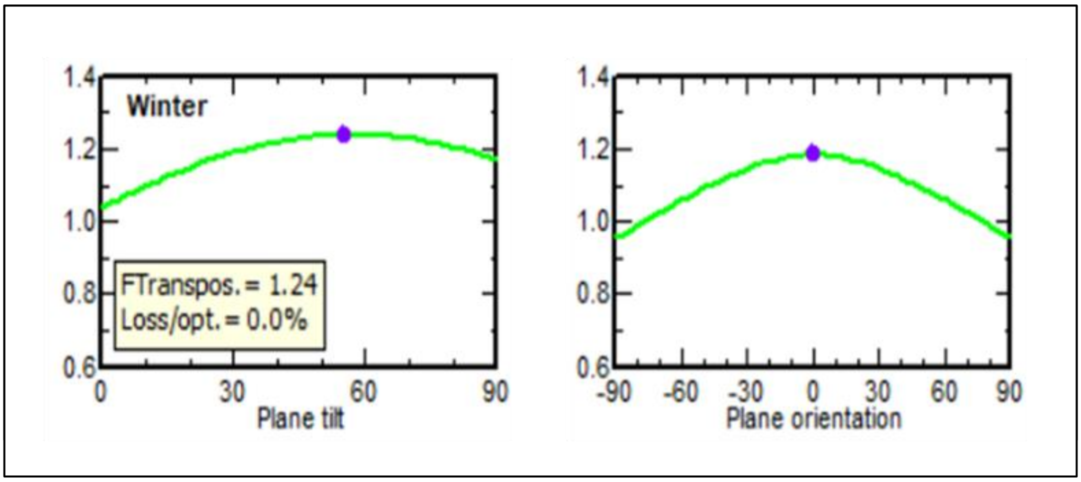


Figure 4.4. Optimization for Plane Tilt and Azimuth Angles with Respect to Yearly Irradiation Yield

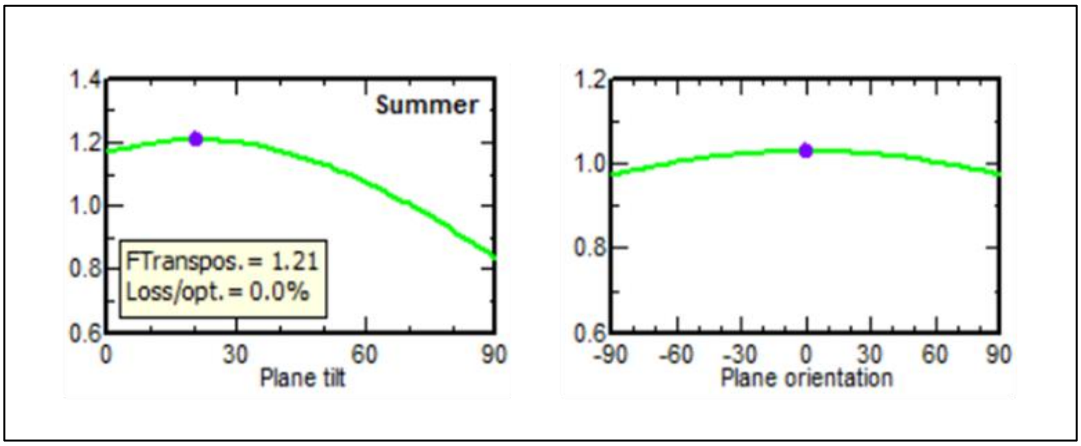
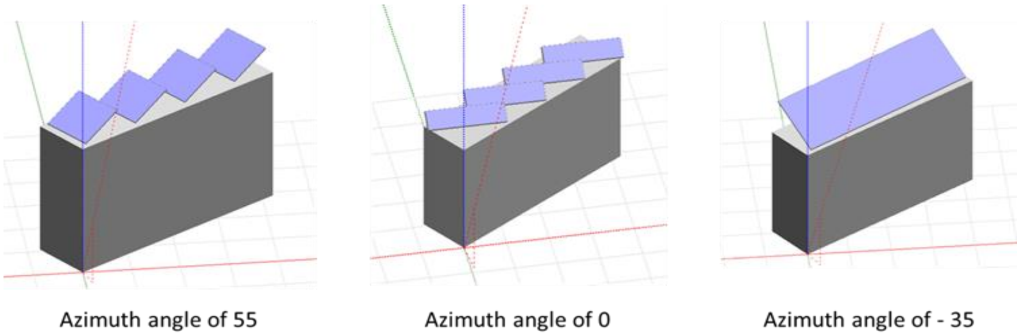


Figure 4.5. Optimization for Plane Tilt and Azimuth Angles with Respect to Summer (April-September) Irradiation Yield

Figure 4.6. Optimization for Plane Tilt and Azimuth Angles with Respect to Winter (October-March) Irradiation Yield

Several simulations were conducted for five chosen buildings with five different azimuth angles (20°, 30°, 55°, 75° and 80°) using the quick simulation tool throughout the year and the results that give the highest yearly energy production varies slightly for each building. Therefore, quick optimization tool has been used for each building to find the optimal tilt angle with respect to three different azimuth angles, first being 0°, second using the same azimuth angle as the building itself and finally the azimuth angle that would result in a right angle with the building.

For each building, simulations were conducted to find the best fitting azimuth angle and tilt angle using the help of pre-sizing help and strings configuration optimizer. In the Figure 4.7, the optimal configurations for Basic English Department B Block, panels with an azimuth angle of 55°, 0° and -35°, and tilt angle of 30°, 35° and 35°respectively are given. The azimuth angle of the building itself is -35 degrees for this building. Number of panels in series and parallel are optimized to achieve the highest production with the help of the PVsyst system optimizer and 3D scene shading modeler.


Azimuth angle of 55

Azimuth angle of 0

Azimuth angle of - 35

Figure 4.7. Panel Placements for Three Different Azimuth Angles for Basic English Department B Block

In the Figure 4.8, Figure 4.9 and Figure 4.10, quick optimization results for title azimuth angles of 55°, 0° and -35° are shown respectively, and the tilt angles resulting in the least loss with respect to optimum. The loss with respect to optimum can never be zero for azimuth angles other than 0° since the zero loss with respect to optimum occurs at 35° of tilt angle and 0° of azimuth angle.

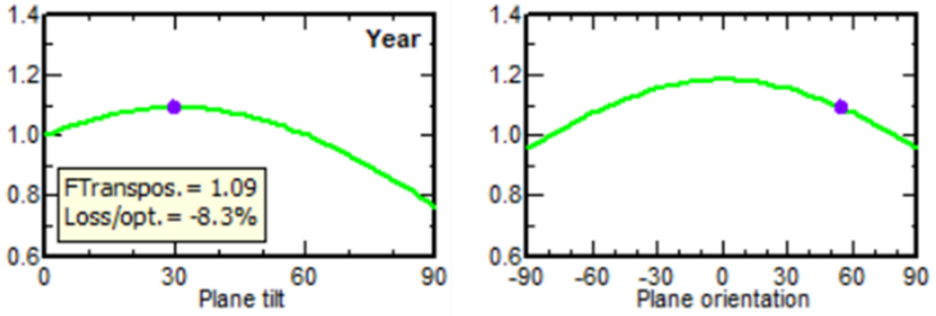


Figure 4.8. Results of Quick Optimization for 55° Azimuth Angle and Tilt Angle of 30°

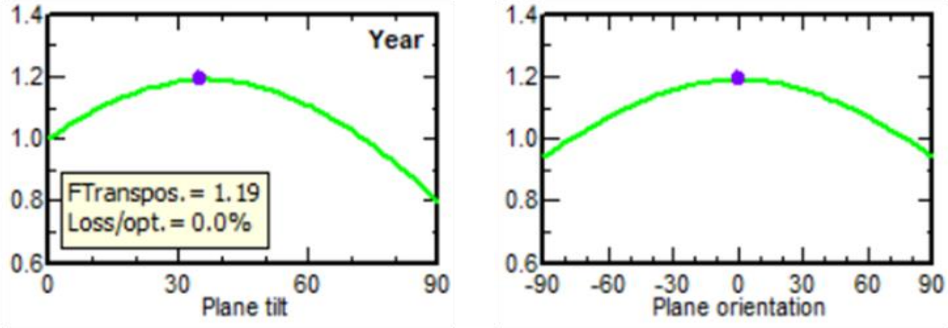


Figure 4.9. Results of Quick Optimization for 0° Azimuth Angle and Tilt Angle of 35°

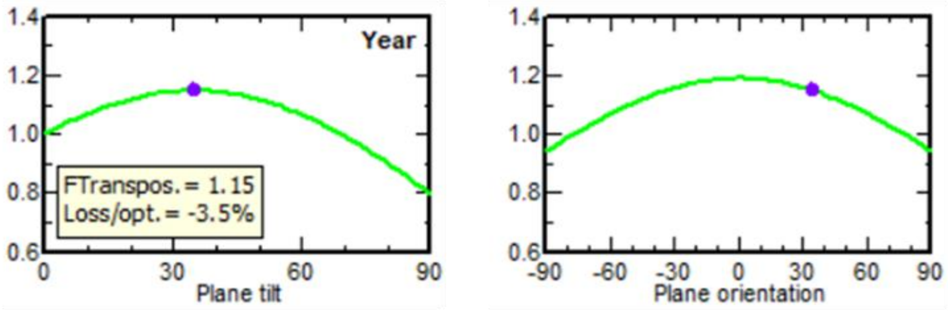


Figure 4.10. Results of Quick Optimization for 35° Azimuth Angle and Tilt Angle of 35°

Since the suitable area for each building changes widely from narrow to wide and from wide side south facing to north facing, conducting this simulation was important to find out how to position the panels. Interestingly, for some buildings placing panels with an angle of 90° was better, but for most, using the same azimuth angle that building has resulted in the highest energy production and an azimuth angle of 0° was the best for a few buildings.

Table 4.1 Optimization Results for the Basic English Department B Block

				System Details		
				Total # of Panels [parallelXseries]	**Total # of Inverters -**	**Inverter Power [kW]**
Azimuth = 0° Tilt = 35°	**Nominal Power**	**[kWp]**	18.9	32 [4x8]	4	5.5
	Energy Output	**[MWh/yr]**	31.4			
	Performance Ratio	-	0.842			
Azimuth = -35° Tilt = 35°	**Nominal Power**	**[kWp]**	37.2	62 [3x21]	3	15
	Energy Output	**[MWh/yr]**	63.7			
	Performance Ratio	-	0.894			
Azimuth=55° Tilt = 30°	**Nominal Power**	**[kWp]**	23.6	4x10	2	9
	Energy Output	**[MWh/yr]**	34			
	Performance Ratio	-	0.797			

In Table 4.1, simulation results for the Basic English Department B Block are shown and the chosen azimuth and tilt angles that results in the highest yearly electricity production is highlighted which has an azimuth angle of 0° and a tilt angle of 35°. Due to the dimensions of the rooftop, systems with panels that have azimuth angles of -35° and 55° have lower number of panels hence lower power output. Same type of simulations were run for all flat roofed buildings and the table of tilt and azimuth angles chosen for panels of each building that yields in the highest power output can be found at Appendix A.

For the pitched rooftops it is assumed that the pitch angle for the roofs is 20°, as Kutlu, (2021) did to calculate the rooftop PV potential of Ankara [57]. And azimuth angles of the panels naturally make right angles with the azimuth angle of the buildings. Meaning that a completely south facing building which would have an azimuth angle of 90° would have panels with an azimuth angle of 0° on one of its sides and panels with an azimuth angle of -90° on its other side.

Result of the quick optimization for the RÜZGEM building rooftop, which is a pitched rooftop without any shadowing elements around, is given in Figure 4.11 for one side of the rooftop having a 120° azimuth angle and in Figure 4.12 for -60°, respectively.

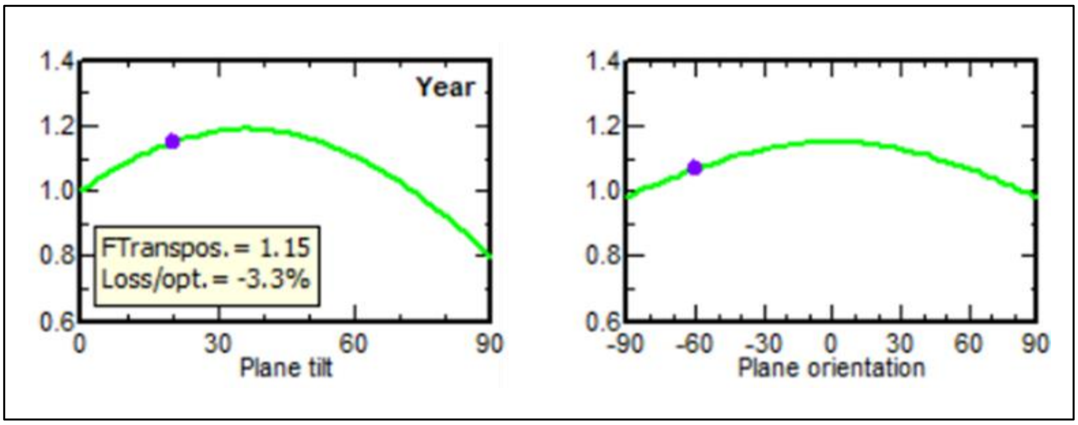


Figure 4.11. Results of Quick Optimization for 120° Azimuth Angle and Tilt Angle of 20°

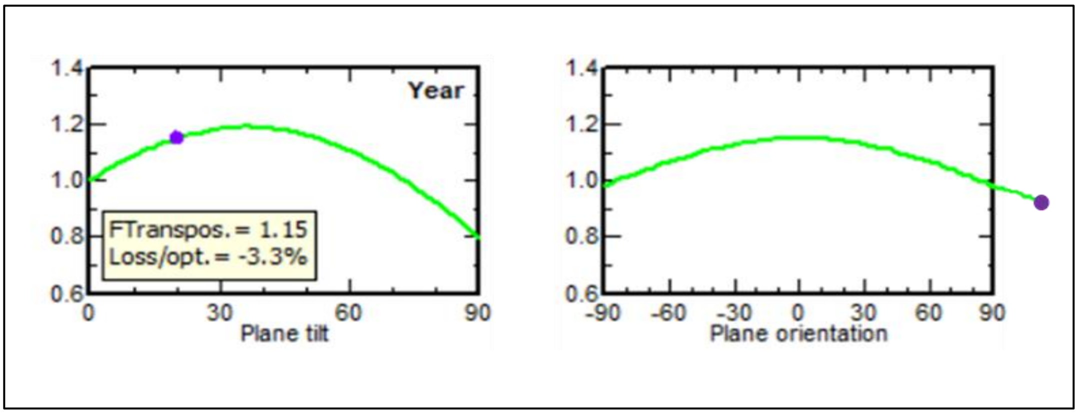


Figure 4.12. Results of Quick Optimization for -60° Azimuth Angle and Tilt Angle of 20°

Table 4.2 Optimization Results for the RÜZGEM Building

				System Details		
				Total # of Panels [parallelXseries]	Total # of Inverters -	Inverter Power [kW]
Azimuth = 120° Tilt = 20°	**Nominal Power**	**[kWp]**	177	600 [6x25]x2*	12	20
	Energy Output	**[MWh/yr]**	230			
	Performance Ratio	-	0.871			
Azimuth = -60° Tilt = 20°	**Nominal Power**	**[kWp]**	177	600 [6x25]x2*	12	20
	Energy Output	**[MWh/yr]**	282			
	Performance Ratio	-	0.884			
TOTAL	**Nominal Power**	**[kWp]**	354	1200	24	20
	Energy Output	**[MWh/yr]**	512			
	Performance Ratio	-	0.875			

Panel placements for the RÜZGEM building are shown in Figure 4.13 and simulation result for the RÜZGEM building is given in Table 4.2. System configurations for both sides of the rooftop and the total system output is given. The system that has -60° of azimuth angle has a 22.6% higher yearly power yield as expected compared to the system with 120° azimuth angle.

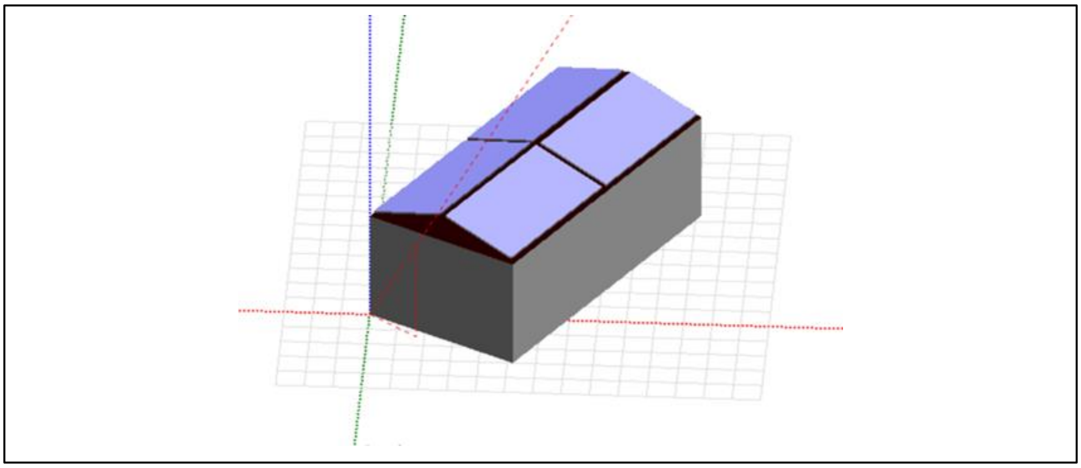


Figure 4.13. Panel Placements for the RÜZGEM Building

4.4.1.2 Detailed System Configurations of Designed Rooftop PV Systems for METU Ankara Campus

Table 4.3 Detailed System Configurations of DBE B Block and RÜZGEM Buildings

Building Name	**-**	**DBE B Block**	**RÜZGEM**
Roof Type	**-**	Flat Roof	Pitched Roof
Horizontal	**[m]**	26.5	15
Vertical	**[m]**	6.6	60
Area	**[m^2]**	174.9	900
Azimuth Angle of the Building	**[°]**	-35	30
Azimuth Angle of the Panels	**[°]**	-35	30
Tilt Angle of the Panels	**[°]**	35	35
Number of Panels in Parallel	**-**	3	6
Number of Panels in Series	**-**	21	25
Total Number of Panels	**-**	63	600
Orientation of Panels	**-**	p	p
Number of Sub-Arrays	**-**	1	4
Number of Inverters (per sub-array)	**-**	3	6
Inverter Power	**[kW]**	15	20
Nominal Power	**[kWp]**	37.2	354
Energy Output	**[MWh/yr]**	63.7	512
PR	**-**	0.894	0.875

In Table 4.3, system configurations for DBE B Block and RÜZGEM buildings are shown including the number of panels in series, strings, number of sub-arrays, number of inverters per series and per sub-array, and inverter power. The detailed system configurations of each building can be found in Appendix A.

The results show that there are hours when PV systems produces more electricity than the campus demand which can be employed if an energy storage system was added to the overall system. The total storage potential for the year is 1813.04 MW and there is an excess electricity production 10.2% of the time. The designed distributed rooftop PV systems for METU Ankara Campus has the total technical electricity output potential of 8419.2 MWh per year which could meet electricity demand of the campus by 30.7%.

4.4.2 Designing the Central Energy Storage System for METU Ankara Campus

METU Ankara Campus as the chosen location for this study is not at a location that would allow pumped hydro storage. The university might not allow or compensate the economical burden of the buildings that has to be constructed for the storage systems that would occupy big spaces such as flywheel, thermal storage or compressed air. Technologies such as fuel cells, superconducting magnetic storage and super-capacitors are still emerging and there are ongoing studies on the compatibility of these storage systems with renewable energy systems conducted by researchers [58-60].

PVsyst offers modeling and simulations of battery storage systems in both lead-acid and lithium-ion technologies. The lithium-ion storage system configuration of PVsyst consist of choosing the system strategy which can be self-consumption, peak shaving or weak grid islanding, choosing the battery system technology, specifying the battery’s manufacturer, determining the number of batteries in parallel and series, initial state of wear in terms of number of cycles and static, establishing the operating temperature, state of charge thresholds, battery input charger and battery to grid inverter configurations, in these order.

It should be noted that modeled battery system is planned to be oversized for the distributed PV systems’ needs. The reason is that the obvious need of renewable energy resource injection to the grid other than solar. The battery system has been modeled in a way that it would allow new additions to the distributed renewable energy systems. In order to achieve higher renewable energy fraction which is the fraction of demand that renewable energy resources can cover, in terms of solar parking lots and empty areas in the campus could be utilized. There are campuses which are close to being fully sustainable that uses several different renewable energy resources for both electricity and heat needs of the campus such as University of California, San Diego Campus which utilizes oversized battery systems [61-63].

Since the campus is considered a medium voltage user by the utility company of Ankara and the electricity is distributed to the campus from one source, modeling a central energy storage system instead of distributed storage systems for each building or area makes less sense in technical and economical terms. Also, consumption data of each building is not available due to the configuration of electricity consumption measurement instruments.

4.4.2.1 Battery System Configuration and Simulations

Table 4.4 Detailed Configuration of the Battery System Used in Modeling

Storage Strategy		-	Self-consumption
Battery Technology		-	Lithium-ion
Manufacturer		-	Tesla
Module Model		-	Powerwall 2
Number of Modules in Series		-	50
Number of Modules in Parallel		-	90
Initial State of Wear (Number of Cycles)		[%]	100
Initial State of Wear (Static)		[%]	100
Operating Battery Temperature	Temperature Mode	-	Average between Tamb and Fixed Temperature
	Fixed Temperature	[°]	20
State of Charge Thresholds	Maximum Charging	[%]	85
	Minimum Discharging	[%]	15
Battery Input Charger	Maximum Charging Power	kW	3000
	Maximum Efficiency	[%]	95
Battery to Grid Inverter	Maximum Discharging Power	kW	4500
	Maximum Efficiency	[%]	95

The detailed battery system configuration modeled for this study is given in Table 4.4 and the battery model used is Tesla Powerwall 2. The spec sheet is given in Appendix B.

Self-consumption scheme fits the model of the study because the goal of modeling an energy system is to meet the demand as much as possible. Tesla Lithium-ion batteries are the most popular lithium-ion batteries that are used in couple with PV systems for residential or commercial use, and the newest model of Powerwall battery series which is Powerwall 2 is the most recommended model [64]. Number of battery modules in series determined so that the maximum charging power would not exceed the maximum power that can be supplied by the PV systems and accordingly output voltage and current. Number of battery modules in parallel determined so that the time of charging during full sun conditions would not exceed the maximum power produced by the PV systems under full sun conditions, hence the battery system would not have an excessively larger capacity than needed. Initial state of wear for both number of cycles and static charge is taken as 100% assuming that the batteries would be brand new. Operating temperature mode is determined to be at an average between ambient temperature and fixed temperature considering the weather conditions of Ankara and the fact that an air conditioning unit would be costly for such model. Fixed temperature is taken as 20° Celsius since most air-conditioning units for these types of applications work in 20°. State of Charge thresholds are determined according to the PVsyst suggestions for lithium-ion batteries used with self-consumption scheme. Maximum charging power is determined according to maximum point of excess electricity which naturally occurs during the day. Maximum discharging power is determined according to the point where electricity supplied by the PV system is at its minimum, which occurs during the night. Maximum efficiencies are left as PVsyst suggests.

Simulations were conducted for the combined the distributed PV systems and a central Lithium-ion battery system. A similar configuration of the infrastructure for the designed system can be seen in Figure 4.14 where the red line can be considered as the main grid that supplies electricity to campus using variety of resources including the petroleum-based fuels, green line could be considered the distributed PV systems and blue lines could be considered as residential, educational, commercial and management buildings of the campus with different electricity consumption profiles [65].

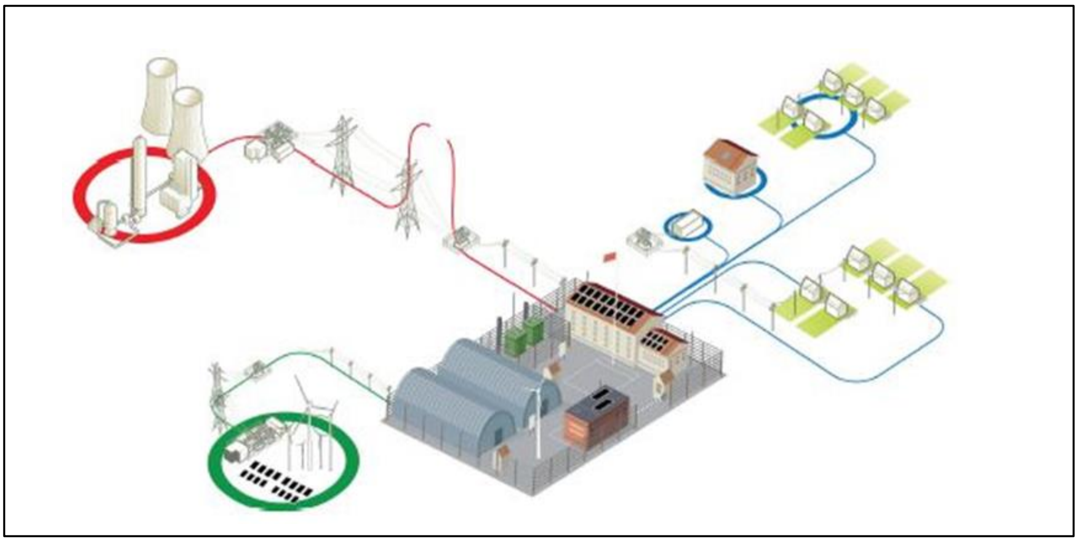


Figure 4.14. Similar Campus Configuration of Electricity Infrastructure

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Simulation Results of Rooftop PV Systems of Selected Buildings

Table 5.1 Simulation Results of RÜZGEM Building

	Array Energy Output [MWh]	System Energy Output [MWh]	System Efficiency [%]	Performance Ratio -
Jan	20.55	20.03	19.79	0.919
Feb	27.24	26.61	19.97	0.927
Mar	40.85	39.93	19.75	0.917
Apr	50.23	49.12	19.24	0.894
May	62.22	60.87	18.81	0.873
Jun	65.37	63.96	18.42	0.856
Jul	67.11	65.66	18.18	0.844
Aug	61.46	60.13	18.14	0.842
Sep	50.41	49.32	18.67	0.867
Oct	35.72	34.91	19.05	0.885
Nov	23.72	23.16	19.39	0.900
Dec	18.29	17.82	19.54	0.907
TOTAL	**523.16**	**511.51**	**18.85**	**0.875**

Simulation results in terms of monthly energy output from array, energy output of the system (after the inverter), performance ratio and system efficiency per array area for both RÜZGEM and DBE B Block are shown in Table 5.1 and Table 5.2 respectively.

Performance ratio of 0.875, total electricity output of 523.16 MWh and an overall system efficiency of 18.85 of the system that was modeled on RÜZGEM building's rooftop indicates that system configuration is quite fitting and good. The system has a normalized production of 3.96 kWh/kWp/day which is also called average final yield in other studies. Compared to studies that covers analysis of real-life rooftop PV applications, the average final yield of this system is quite satisfactory for the region of the study [66]. The specific production of the system is 1445 kWh/kWp/year. It should be noted that the available rooftop area is calculated as 900 m².

Table 5.2 Simulation Results of DBE B Block

	Array Energy Output [MWh]	**System Energy Output [MWh]**	**System Efficiency [%]**	**Performance Ratio -**
Jan	3.50	3.41	20.80	0.965
Feb	4.22	4.13	20.70	0.961
Mar	5.39	5.00	19.30	0.894
Apr	5.99	5.85	19.80	0.921
May	6.92	6.76	19.50	0.904
Jun	6.84	6.69	19.10	0.886
Jul	7.19	7.03	18.80	0.873
Aug	7.13	6.47	17.40	0.809
Sep	6.66	6.33	18.70	0.869
Oct	5.28	5.06	19.30	0.897
Nov	3.99	3.77	19.50	0.908
Dec	3.25	3.18	20.70	0.960
TOTAL	**66.36**	**63.67**	**19.30**	**0.894**

The system modeled on top of the DBE B Block has a yearly energy production of 63.67 MWh with an efficiency of 19.30 and a yearly performance ratio of 0.894. Specific production and normalized production of the system are 1713 kWh/kWp/year and 4.69 kWh/kWp/day respectively. It is apparent from overall system efficiency, performance ratio, specific production and normalized production that the system of DBE B Block works better than the RÜZGEM one. The main reason is the fact that, RÜZGEM has a pitched roof and the panels on the north facing side has a lower efficiency. This comparison result can also be observed on other pitched roofed buildings.

The system behavior difference between flat roofed systems and pitched roofed systems are more obvious if the monthly electricity output graphs of RÜZGEM and DBE B Block are compared. These graphs are given in Figure 5.1 and Figure 5.2 respectively.

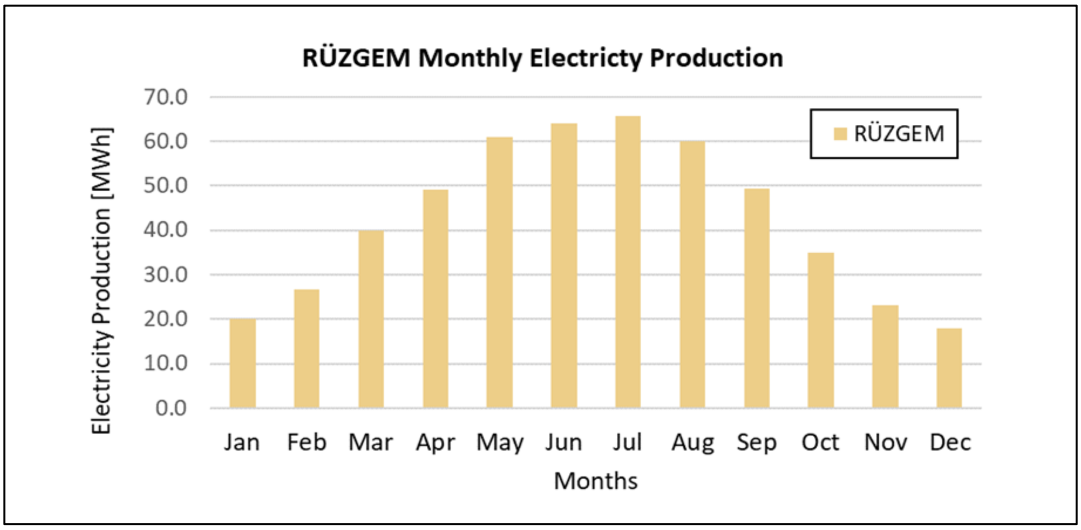


Figure 5.1. RÜZGEM Monthly Electricity Output

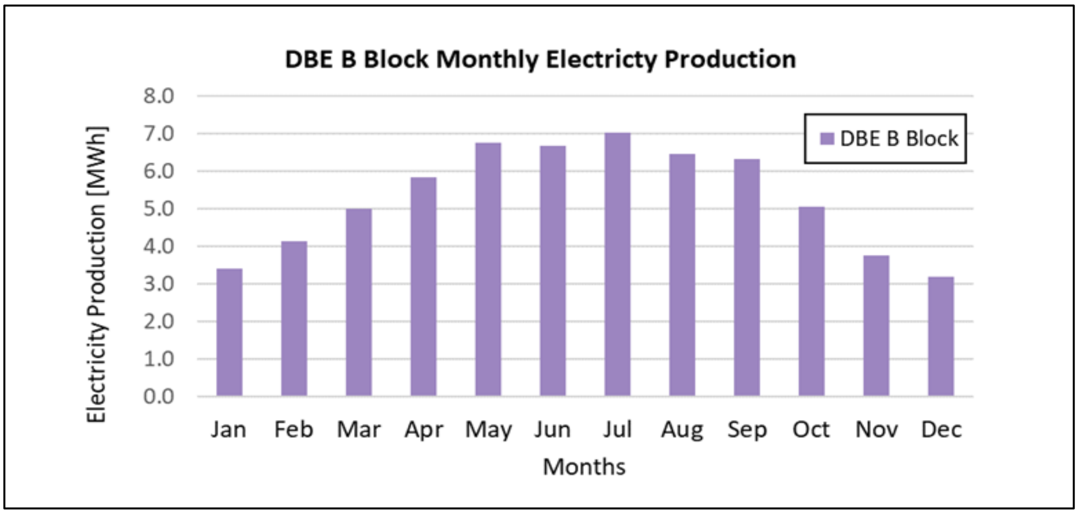


Figure 5.2. DBE B Block Monthly Energy Output

The electricity production of the DBE B Block system does not spike up as RÜZGEM system does. There could be several reasons for this difference in system behavior. First one is that azimuth angle of the panels of DBE B Block is -35° and for RÜZGEM half of the panels have an azimuth angle of 120° and the other half has -60°. Second one is that related to seasonal sun position. Due to the location chosen for this study, during summer sun follows a straighter path compared to winters, meaning that during summer months panels on both side of the RÜZGEM building can produce far more electricity compared to winter However, DBE B Block has higher shading loss during summer due to the panel orientation.

5.2 Simulation Results of Sum of All Rooftop PV Systems

The sum of monthly output of all systems are given in Figure 5.3. The total output of the system is 8419.2 MWh.

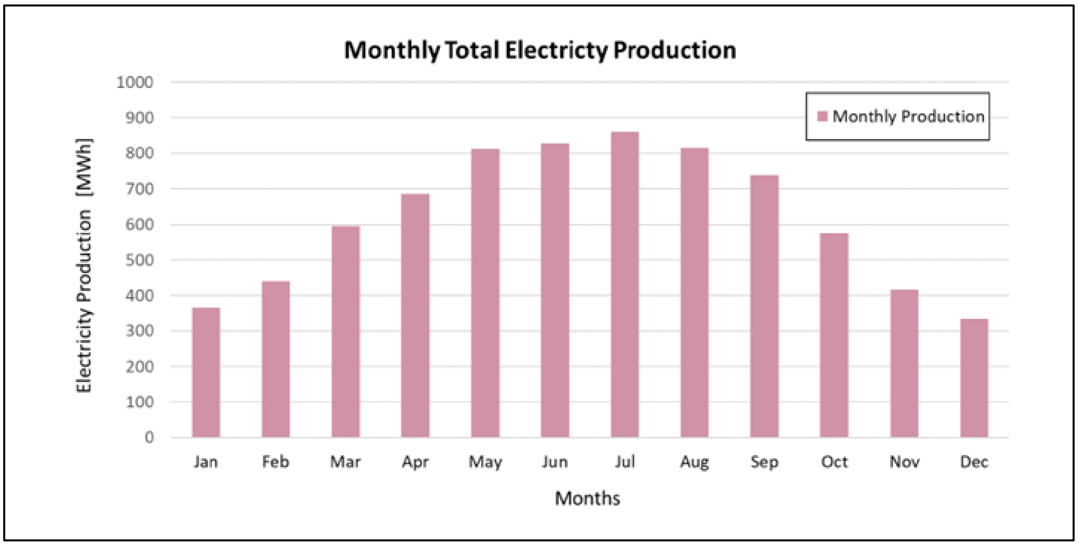


Figure 5.3. Monthly Electricity Production of Sum of All Systems

The comparison of the total PV output and total consumption is given in Figure 5.4.

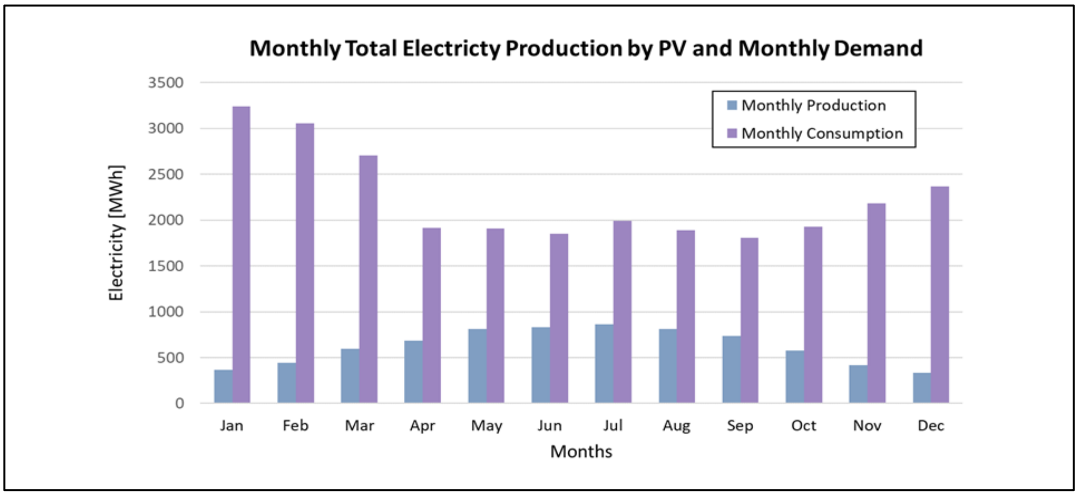


Figure 5.4. Monthly Production by Rooftop PV Systems and Monthly Campus Demand

The graphs show that the sum of all system cannot produce enough electricity to meet the consumption of the campus even in summer where the consumption is lower compared to other seasons and PV production is at its highest. However, campus has a constant base hourly demand including the night. Therefore, checking how much of the hourly demand and daily consumption was met by the PV production is important. For better clarity, the daily consumption and production are presented in Figure 5.5.

Since the systems cannot produce electricity during the night, it is important to analyze the competence of the system in terms of meeting the demand. In Figure 5.6, the monthly production and consumption are shown during the day (i.e., sun hours, from 6 AM to 7PM) also the percentages are included.

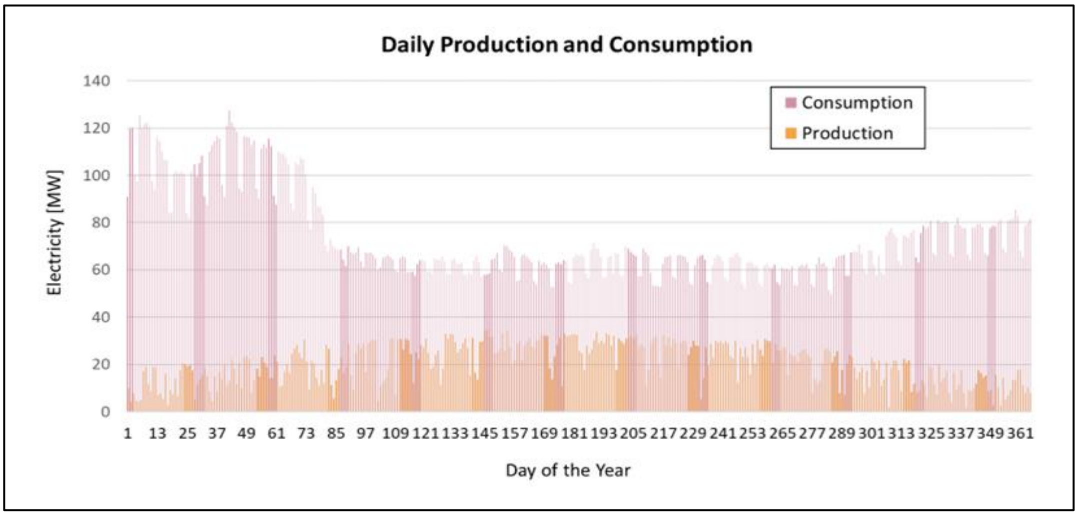


Figure 5.5. Daily Consumption and Production

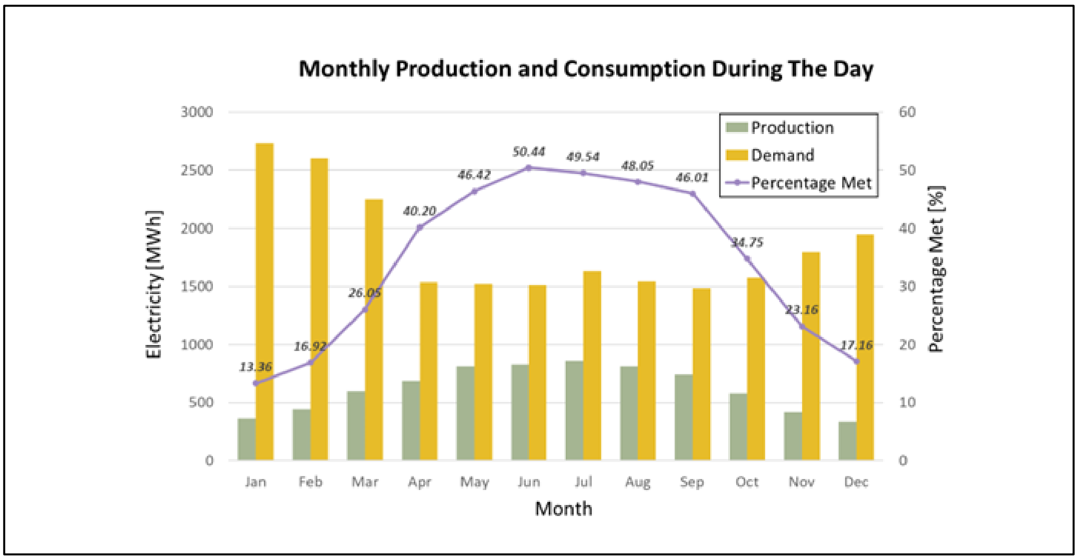


Figure 5.6. Monthly Production of All Systems and Consumption During the Day (from 6 AM to 7PM)

As expected during the summer systems have the capacity to meet half of the consumption. However monthly values cannot represent the simulations that were run in 1-hour intervals for a whole year. Therefore, in order to grasp how the system performs, the hourly percentages met by the production during the day are given in Figure 5.7. The graph shows that there are hours that PV systems produces more electricity than the campus demand which can be employed if an energy storage system was added to the overall system.

5.3 Simulation Results of the Combined Systems

The daily electricity supplied to the user from battery is shown in Figure 5.8. It should be noted that battery system is modeled so that there would not be any electricity trade from campus's system to the main grid. The total energy stored and discharged from the battery system to the campus grid for a year of simulation is 941.95 MW.

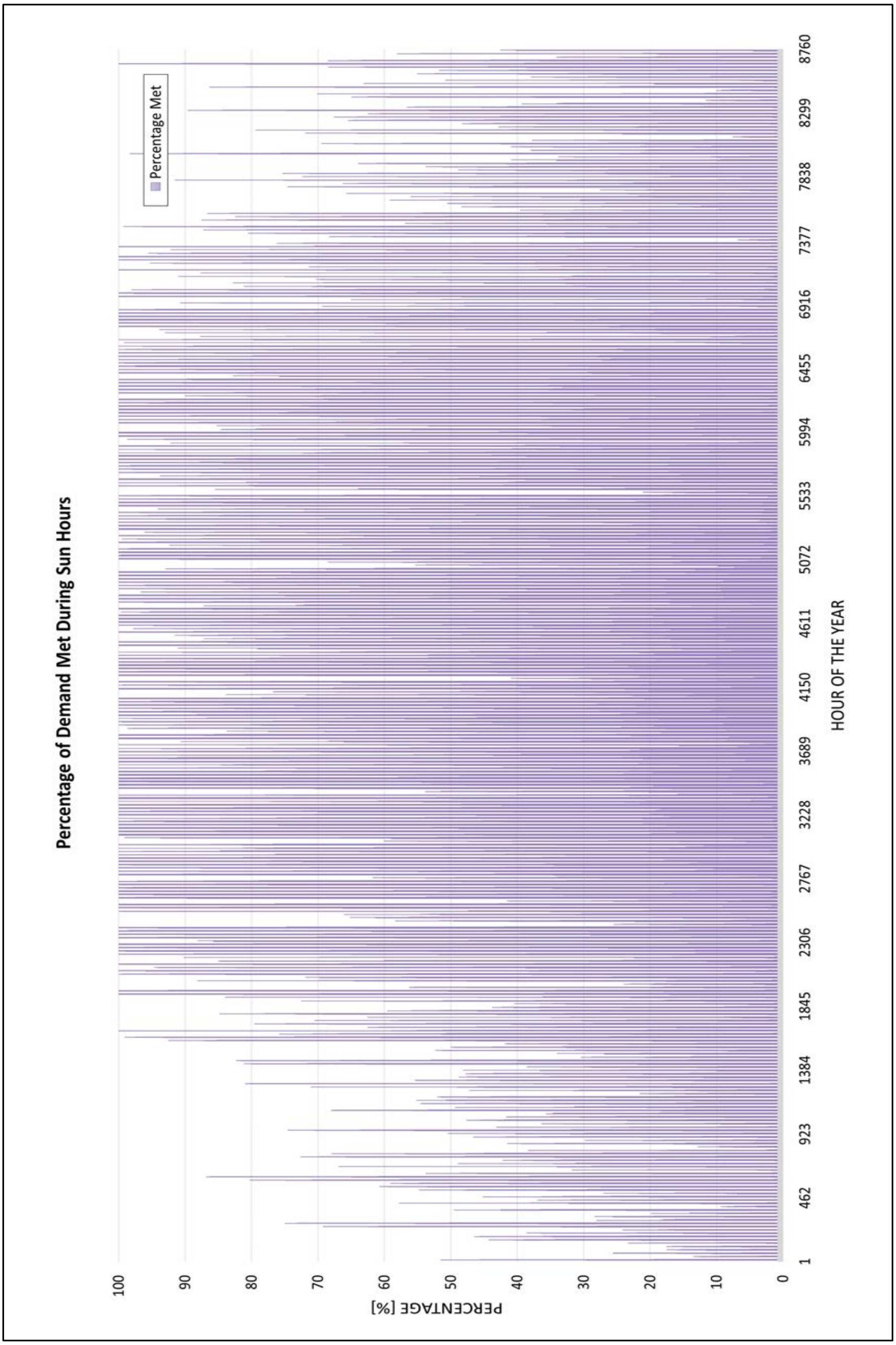


Figure 5.7. Percentage of Hourly Demand Met During the Day Hours

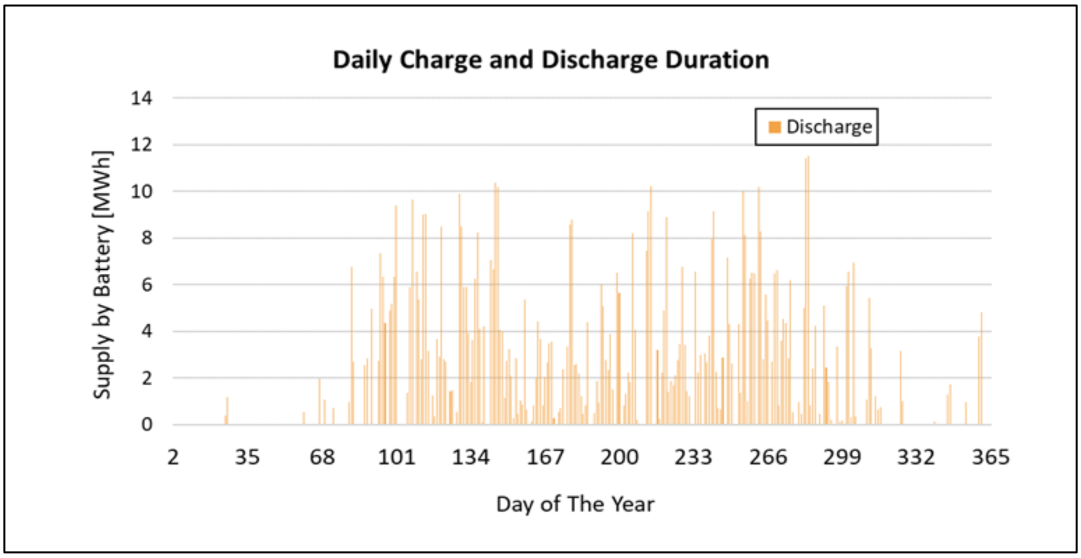


Figure 5.8. Daily Electricity Supply from the Battery System to Campus

The majority of excess power production from PV systems was expected to happen during summer where there would be higher solar irradiation. However, as it is shown in Figure 5.8, battery system is able to supply excess electricity to campus and better utilize the potential of the distributed PV systems. The duration of daily charge and discharge is given in Figure 5.9. Discharging duration is significantly lower for majority of days. The reason is that the discharging under maximum load was predicted by the PVsyst software battery module as 6.4 hours and discharging under average load as 15.9 hours however most of the discharging happens during the night where the load is close to the average load, hence the stored energy is not enough to supply the whole demand during the night. In Figure 5.10, the percentage of daily demand met by the combined system is shown.

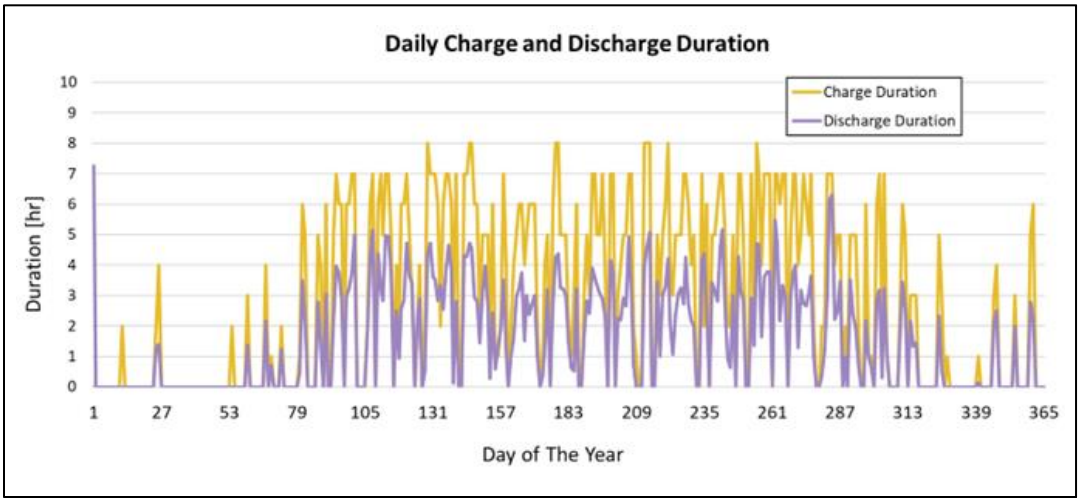


Figure 5.9. Daily Charge and Discharge Duration of the Battery System

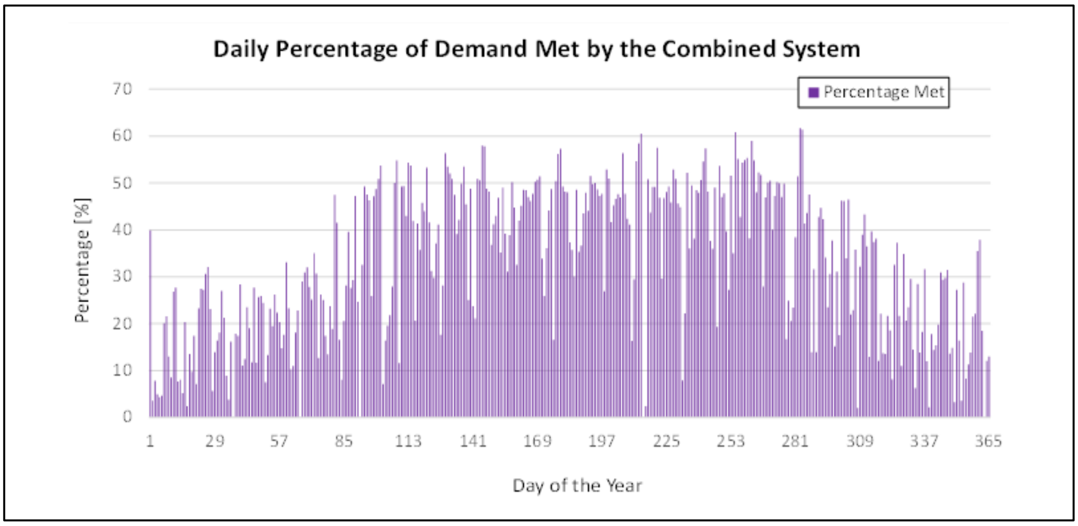


Figure 5.10. Daily Percentage of Demand Met by the Combined System

Therefore, it can be concluded that the combined system never meets the need of the campus in daily terms. The main reason is that the distributed PV systems as modeled in this study would never produce enough electricity that would be enough to meet the electricity needs of the campus. Recurrently, it is needed to employ electricity producing technologies that uses other means of renewable energy or a solar power plant that expends over the available rooftops of the campus.

In Figure 5.11, the state of wear of the battery system due to cycling and aging is presented. This data shows that there might rise a need to renew the battery systems after 5 to 6 years which is normal for such systems however it might be considered to be costly.

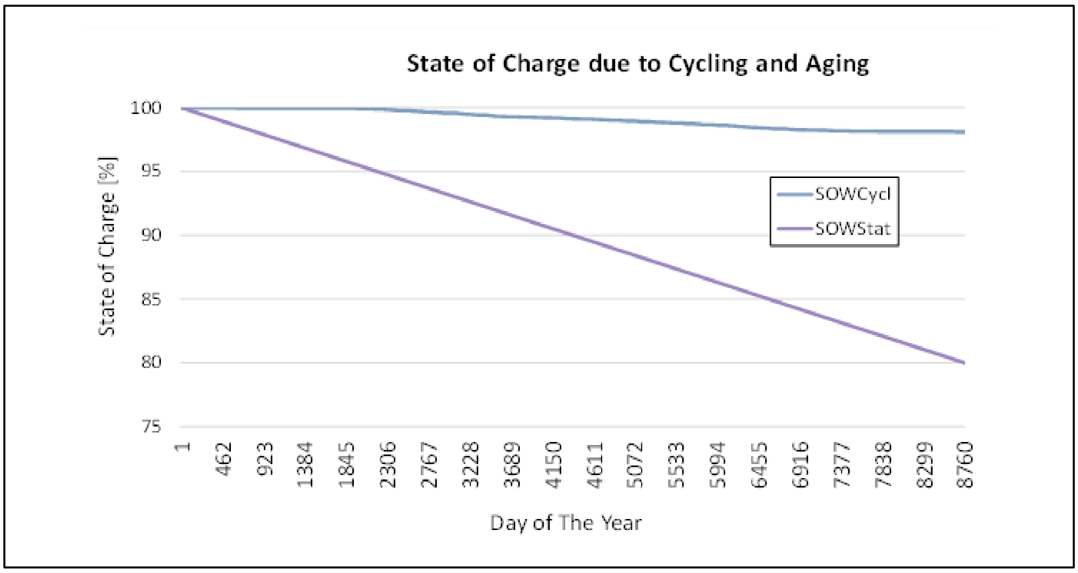


Figure 5.11. State of Charge of the Battery System due to Cycling and Aging

In the Figure 5.12, daily total electricity production of the combined system, electricity supplied from the grid and the user demand are presented. Monthly supply and demand is given in Figure 5.13. Comparing Figure 5.13 and Figure 5.4, it is apparent that the battery system balances the natural seasonal intermittency of distributed PV systems. Comparison of Figure 5.12 and Figure 5.5 confirms that the overall percentage of demand met increases especially during the winter months.

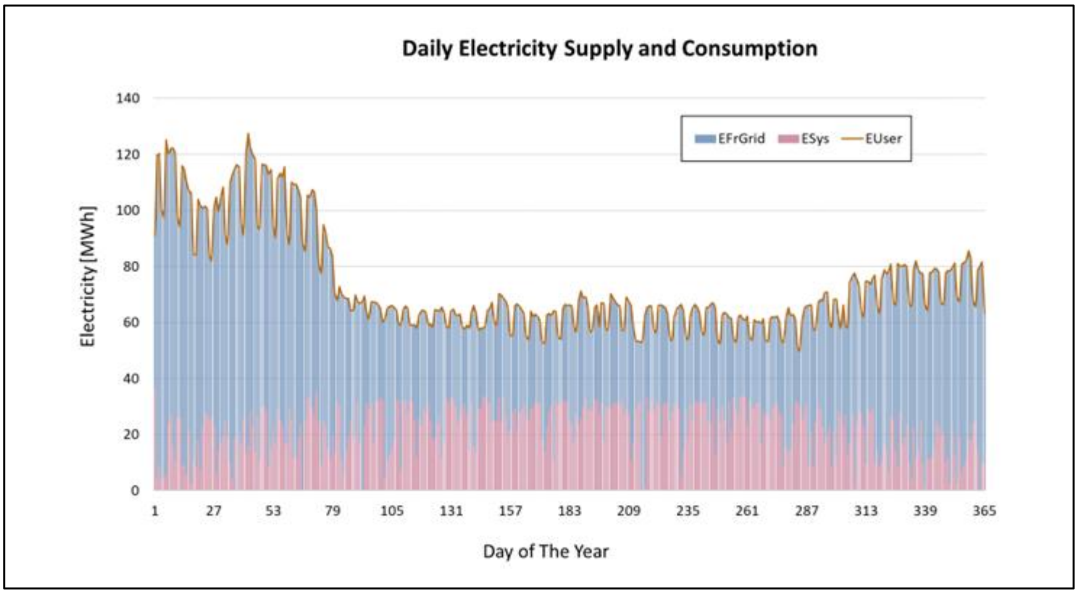


Figure 5.12. Daily Electricity Supplied by the Combined System and Campus Consumption

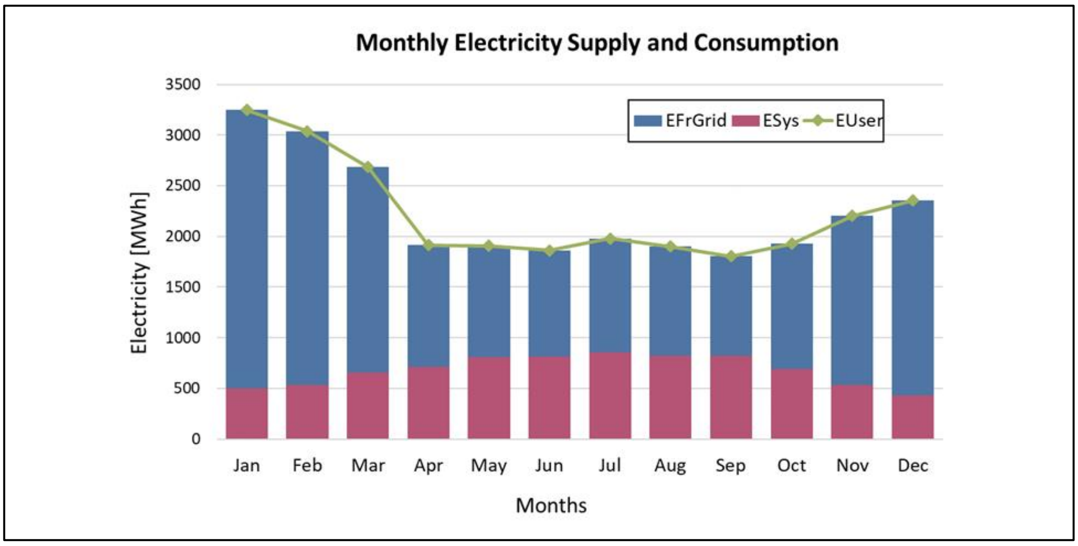


Figure 5.13. Monthly Electricity Supplied by the Combined System and Campus Consumption

It is visibly clear in Figure 5.12 that there are some unexpected drops in demand. These are the 1% of the year where software predicts system maintenance or failure, the random chosen data points result in a loss of 156.56 MW per year.

The performance ratio of the overall system is 0.887 which is higher than the average of performance ratios of all distributed PV systems. The nominal power of all the distributed PV systems is 4673 kWp. The renewable energy ratio of the system, which is the ratio of renewable energy use to total energy use of a system, is 29.82%. The monthly system efficiency is presented in Figure 5.14. The average yearly efficiency of the combined system is 19.10% which is in agreement with similar studies conducted using both PVsyst and other software [67-70]. The combined systems meet the 29.82% of the consumption of the campus. Therefore, it can be concluded that the addition of the energy storage system realized its design goal which was to employ the total electricity potential created by production of the rooftop PV systems. The loss of 0.88% between the potential and combined system's demand met percentage is due to battery losses.

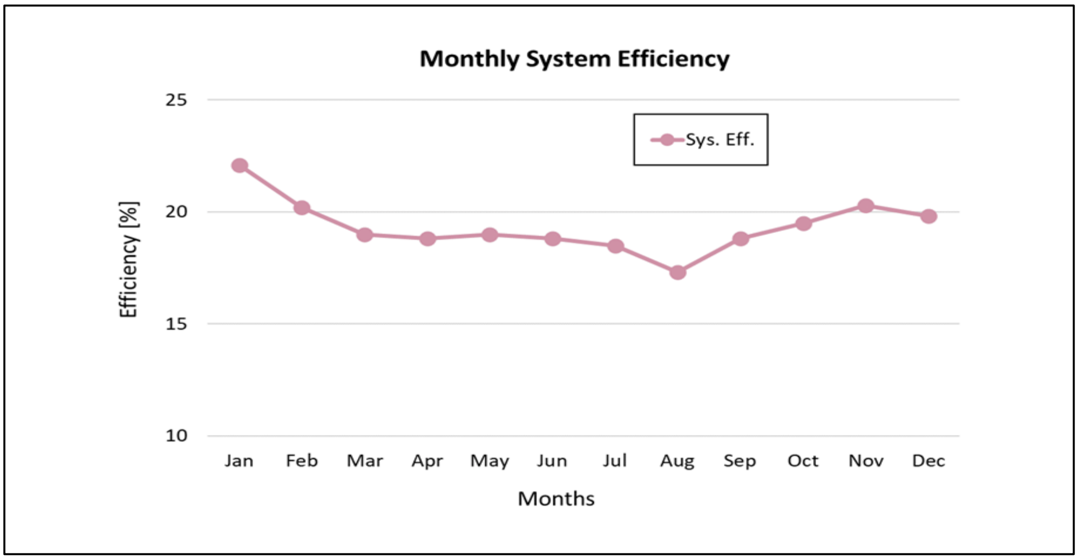


Figure 5.14. Monthly System Efficiency of the Combined Systems

In Figure 5.15, the direct use from PV systems, the energy injected to campus grid by the combined systems and overall system loss in monthly terms are given for clear comparison. The area between the two lines of direct use and supply is the energy stored in the battery system.

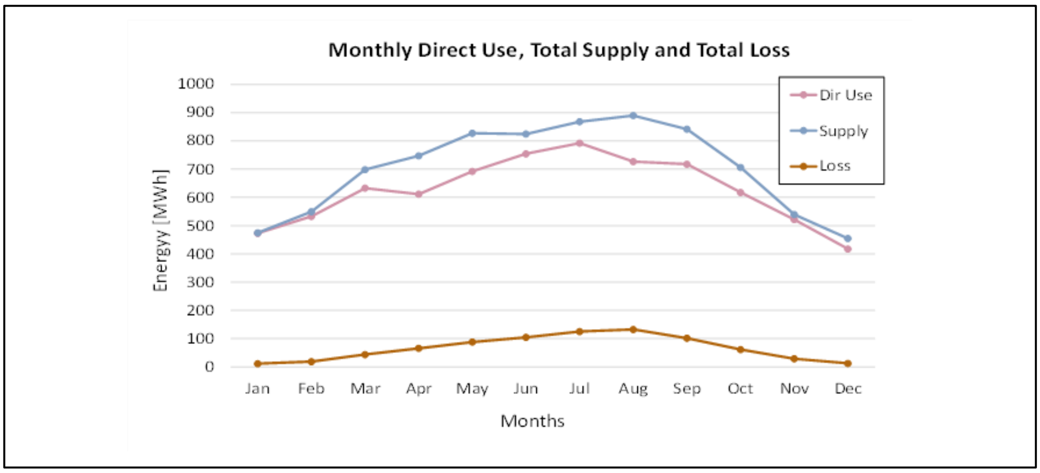
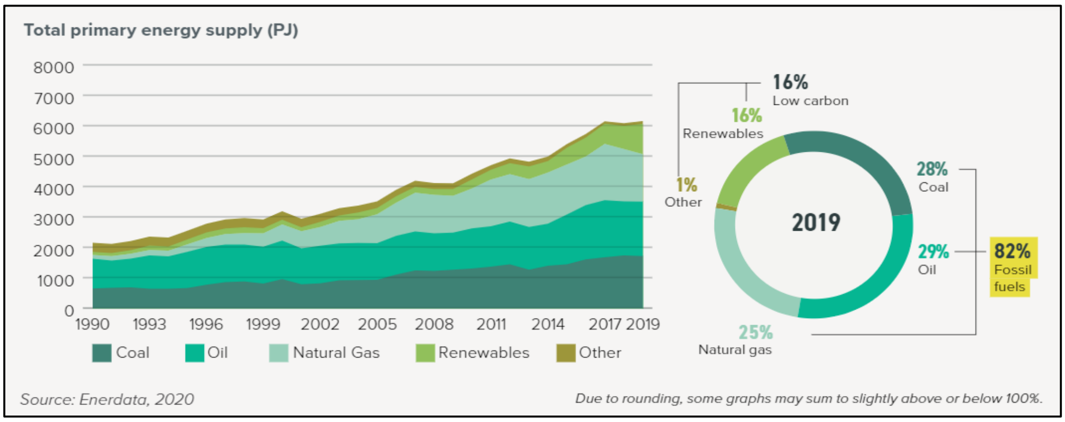


Figure 5.15. Monthly Direct Use of Energy from PV Production, Total Supply and Overall Loss

System losses include near shading losses, loss due to albedo, PV loss due to irradiance level, PV loss due to temperature, optimizer losses, module quality loss, module mismatch loss, ohmic wiring losses, inverter loss during operation, inverter loss due to power threshold and voltage threshold, inverter loss over nominal inverter power and voltage, inverter loss due to maximum input current, battery charger and inverter loss. Near Shading losses are included in the simulations by using the near shading simulator of PVsyst, array and inverter losses are calculated by the module layout feature of the software, battery losses are calculated by the software without any user-interface.

In Figure 5.16, Turkey’s energy mix and in Figure 5.17 Carbon Intensity of Turkey’s Energy Sector as given in Climate Transparency Report 2020 are presented respectively [71]. As given in Figure 5.17, 61.22 tons of CO_2 is emitted per 1 TJ of energy supply. Hence, the modeled and simulated systems for METU Ankara campus would help Turkey avoid 1826.23 tons of CO2 emissions.

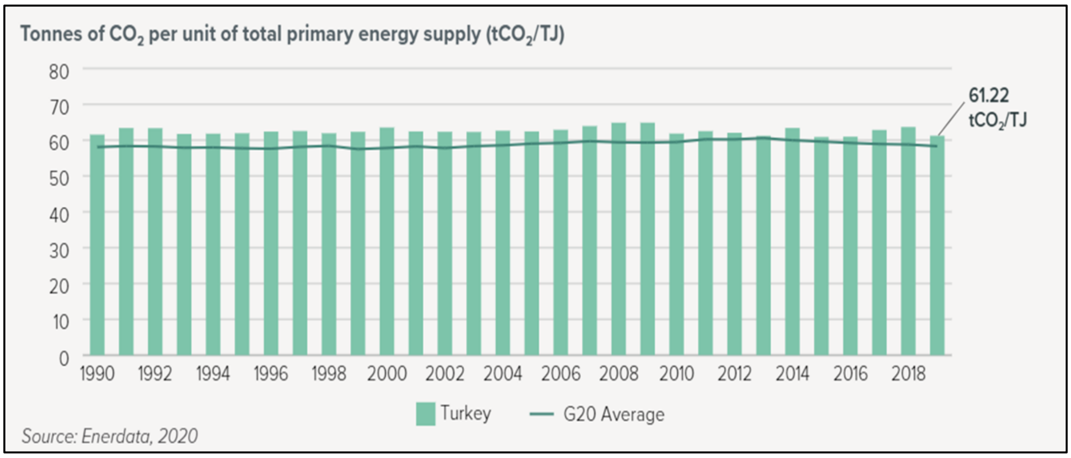


Total primary energy supply (PJ)

Source: Enerdata, 2020

Due to rounding, some graphs may sum to slightly above or below 100%.

Figure 5.16. Turkey’s Energy Mix



Tonnes of CO_2 per unit of total primary energy supply (tCO_2/TJ)

Source: Enerdata, 2020

Figure 5.17. Carbon Intensity of Turkey’s Energy Sector

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Recently, researchers focused on the subject of renewable energy technologies due to increasing energy demand and resource depletion caused by climate change and increasing population. In this thesis study, a guideline for modeling and simulation of multiple rooftop PV systems and energy storage system (or systems) that form a combined hybrid system were developed. The series of methods given here can be adopted to model and simulate rooftop PV systems for one or multiple types of rooftops as decentralized or central energy generation systems and energy storage systems. As a case study, the guideline has been employed, multiple decentralized PV systems and a centralized battery storage system were modeled, and simulations were conducted for METU Ankara campus for a year with one-hour time intervals with the goal of meeting the hourly electricity demand of the campus, using the PVsyst software.

The main findings of this study is that the METU Ankara Campus has technical potential for distributed PV systems that could reach the energy output of 8419.2 MWh per year which could meet electricity demand of the campus by 30.7%. With utilization of Lithium-ion battery systems, modeled combined systems of distributed PV and battery system is able to provide 29.82% of the consumed electricity. Efficiency of the combined system is 19.10% and performance ratio is 0.887. The modeled and simulated combined system for the METU Ankara Campus would help the area avoid 1826.23 tons of CO2 emissions. Results show that this is a promising system design and technically feasible, however rooftops of the campus even combined with a strong battery system can never be enough to meet the electricity demand of the campus fully.

6.2 Future Work

Further studies can be conducted on the adding other renewable energy production technologies such as solar thermal and wind to the technical feasibility methodology given in this study. Detailed studies on the electrical grid configuration of the studied area would improve the electrical feasibility of the study. Also extending this study to include economical aspects of the modeled systems should be considered. Economical feasibility aspect of this study is important if efforts in making METU Ankara Campus more sustainable comes to switching from main grid, which uses carbon-based fuels more than renewable energy resources, to distributed renewable energy resources. Environmental impact of the modeled and simulated systems should also be considered for further studies, so the secondary key contributions of the study can be broadened. For the METU Ankara Campus part of the study, modeling the individual electricity consumption of each building which was included in this study can be considered as the immediate next step of this study.

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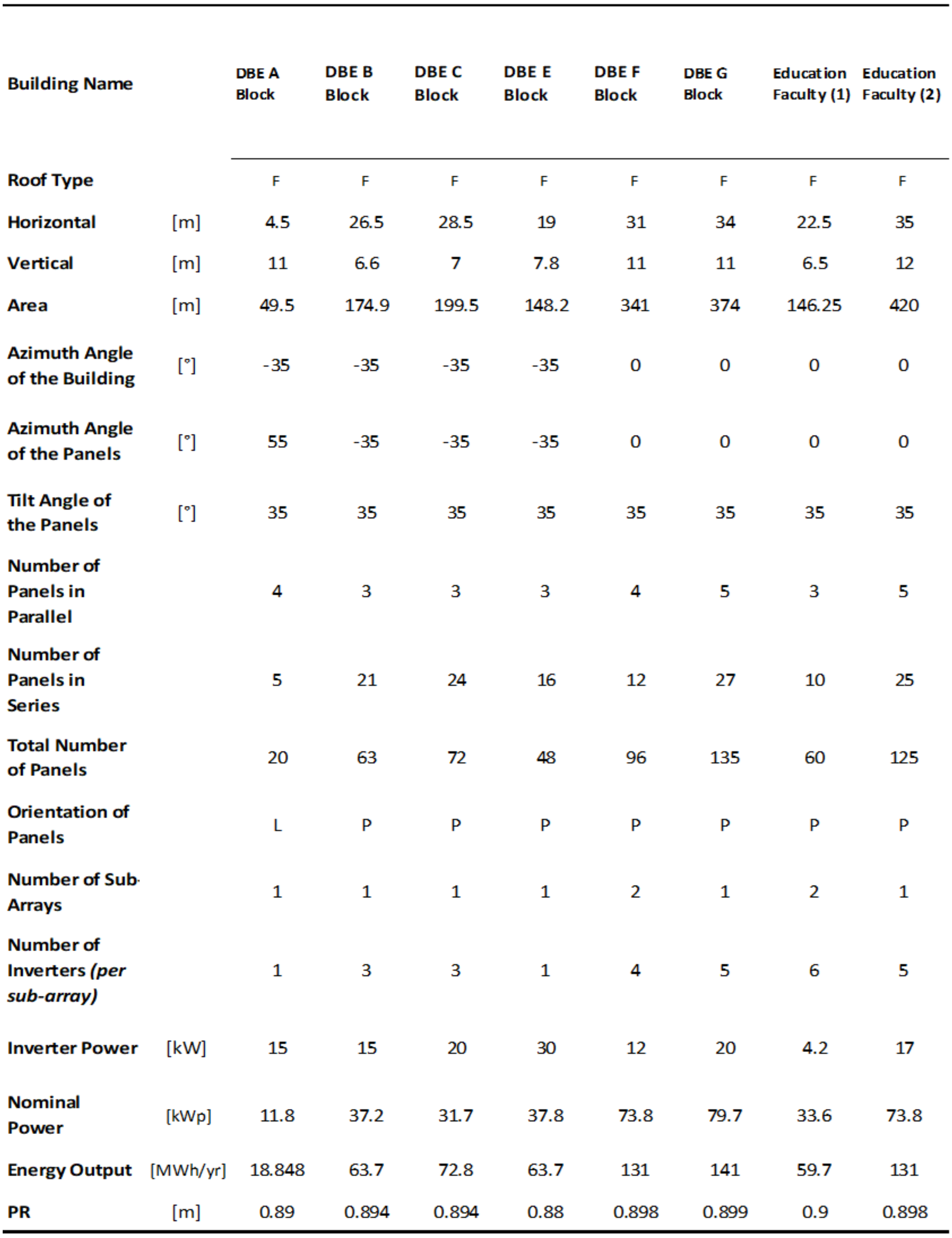
APPENDICES

A. Detailed System Configurations and Simulation Results of PV Systems



Building Name		DBE A Block	DBE B Block	DBE C Block	DBE E Block	DBE F Block	DBE G Block	Education Faculty (1)	Education Faculty (2)
Roof Type		F	F	F	F	F	F	F	F
Horizontal	[m]	4.5	26.5	28.5	19	31	34	22.5	35
Vertical	[m]	11	6.6	7	7.8	11	11	6.5	12
Area	[m]	49.5	174.9	199.5	148.2	341	374	146.25	420
Azimuth Angle of the Building	[°]	-35	-35	-35	-35	0	0	0	0
Azimuth Angle of the Panels	[°]	55	-35	-35	-35	0	0	0	0
Tilt Angle of the Panels	[°]	35	35	35	35	35	35	35	35
Number of Panels in Parallel		4	3	3	3	4	5	3	5
Number of Panels in Series		5	21	24	16	12	27	10	25
Total Number of Panels		20	63	72	48	96	135	60	125
Orientation of Panels		L	P	P	P	P	P	P	P
Number of Sub-Arrays		1	1	1	1	2	1	2	1
Number of Inverters *(per sub-array)*		1	3	3	1	4	5	6	5
Inverter Power	[kW]	15	15	20	30	12	20	4.2	17
Nominal Power	[kWp]	11.8	37.2	31.7	37.8	73.8	79.7	33.6	73.8
Energy Output	[MWh/yr]	18.848	63.7	72.8	63.7	131	141	59.7	131
PR	[m]	0.89	0.894	0.894	0.88	0.898	0.899	0.9	0.898

Building Name		**GISAM**	**Economy (1)**	**Economy (2)**	**Social Sciences (1)**	**Social Sciences (2)**	**MATH**	**Rectorship (lower)**	**Rectorship (higher)**
Roof Type		F	F	F	F	F	F	F	F
Horizontal	[m]	9	20	15.5	7	18	20	15.5	9
Vertical	[m]	13	7	17	23	6.5	7	8	9
Area	[m]	117	140	263.5	161	117	140	124	81
Azimuth Angle of the Building	[°]	0	0	0	0	0	0	0	0
Azimuth Angle of the Panels	[°]	-90	-90	0	90	0	0	0	0
Tilt Angle of the Panels	[°]	35	35	35	35	35	35	35	35
Number of Panels in Parallel		4	3	3	3	3	3	3	2
Number of Panels in Series		11	16	12	20	15	17	13	14
Total Number of Panels		44	48	72	60	45	51	39	28
Orientation of Panels		P	P	P	P	P	P	P	P
Number of Sub-Arrays		1	1	2	1	1	1	1	1
Number of Inverters *(per sub-array)*		2	3	2	3	3	3	3	2
Inverter Power	[kW]	14.4	10	9	15	10	10	9	10
Nominal Power	[kWp]	26	28.3	42.5	35.4	26.6	30.1	23	16.5
Energy Output	[MWh/yr]	35.7	49.9	71.6	50.7	46.7	53.2	40.1	29
PR	[m]	0.883	0.894	0.855	0.896	0.892	0.896	0.883	0.889

Building Name		Chemistry	Central Engineering	EE B,C,D Block	EE A Block	CENG (1)	CENG(2)	Computer Center	CE K1 (1)
Roof Type		F	F	F	F	F	F	F	P
Horizontal	[m]	30	22	37	13.5	12	14	9	14.5
Vertical	[m]	6.5	15	5	10.5	10	5.5	24	18
Area	[m]	195	330	185	141.75	120	77	216	261
Azimuth Angle of the Building	[°]	0	35	0	0	0	0	0	-90
Azimuth Angle of the Panels	[°]	0	35	0	0	0	0	90	-90
Tilt Angle of the Panels	[°]	35	35	35	35	35	35	35	20
Number of Panels in Parallel		3	3	4	5	2	3	4	6
Number of Panels in Series		25	10	15	11	20	12	18	15
Total Number of Panels		75	120	60	55	40	36	72	90
Orientation of Panels		P	P	P	P	P	P	P	P
Number of Sub-Arrays		1	4	1	1	1	1	1	1
Number of Inverters *(per sub-array)*		3	1	4	5	2	1	4	3
Inverter Power	[kW]	15	12	10	9	15	14.4	10	20
Nominal Power	[kWp]	44.3	50.4	35.4	32.5	23.6	15.8	42.5	53.1
Energy Output	[MWh/yr]	78.4	80.238	62.2	56.5	41.9	27.753	60.7	79.1
PR	[m]	0.898	0.831	0.892	0.884	0.9	0.889	0.895	0.893

Building Name		Chemistry	Central Engineering	EE B,C,D Block	EE A Block	CENG (1)	CENG(2)	Computer Center	CE K1 (1)
Roof Type		F	F	F	F	F	F	F	P
Horizontal	[m]	30	22	37	13.5	12	14	9	14.5
Vertical	[m]	6.5	15	5	10.5	10	5.5	24	18
Area	[m]	195	330	185	141.75	120	77	216	261
Azimuth Angle of the Building	[°]	0	35	0	0	0	0	0	-90
Azimuth Angle of the Panels	[°]	0	35	0	0	0	0	90	-90
Tilt Angle of the Panels	[°]	35	35	35	35	35	35	35	20
Number of Panels in Parallel		3	3	4	5	2	3	4	6
Number of Panels in Series		25	10	15	11	20	12	18	15
Total Number of Panels		75	120	60	55	40	36	72	90
Orientation of Panels		P	P	P	P	P	P	P	P
Number of Sub-Arrays		1	4	1	1	1	1	1	1
Number of Inverters *(per sub-array)*		3	1	4	5	2	1	4	3
Inverter Power	[kW]	15	12	10	9	15	14.4	10	20
Nominal Power	[kWp]	44.3	50.4	35.4	32.5	23.6	15.8	42.5	53.1
Energy Output	[MWh/yr]	78.4	80.238	62.2	56.5	41.9	27.753	60.7	79.1
PR	[m]	0.898	0.831	0.892	0.884	0.9	0.889	0.895	0.893

Building Name		**ENVE**	**METE A,B,C**	**METE D**	**GEOE**	**RÜZGEM**	**West Dorms***	**ME D Block**	**ME E Block**
Roof Type		F	F	F	F	P	F	F	P
Horizontal	[m]	24	28.5	13.5	14	15	31	13.5	0
Vertical	[m]	11.5	4	21	10	60	10	18.5	0
Area	[m]	276	114	283.5	140	900	310	249.75	0
Azimuth Angle of the Building	[°]	0	15	15	15	30	-20	0	0
Azimuth Angle of the Panels	[°]	0	15	15	15	30	-20	0	0
Tilt Angle of the Panels	[°]	35	36	36	36	35	36	35	35
Number of Panels in Parallel		4	3	2	4	6	8	3	11
Number of Panels in Series		20	12	11	12	25	12	12	12
Total Number of Panels		80	36	66	48	600	96	72	264
Orientation of Panels		P	L	P	P	P	P	P	P
Number of Sub-Arrays		1	1	3	1	4	1	2	2
Number of Inverters *(per sub-array)*		4	3	3	4	6	4	3	11
Inverter Power	[kW]	15	9	15	9	20	14.4	9	9
Nominal Power	[kWp]	47.2	21.2	38.9	28.3	354	679.2	42.5	156
Energy Output	[MWh/yr]	82.7	35.3	65.6	48.1	512	1168.8	73.1	220
PR	[m]	0.889	0.869	0.863	0.87	0.875	0.879	0.873	0.861

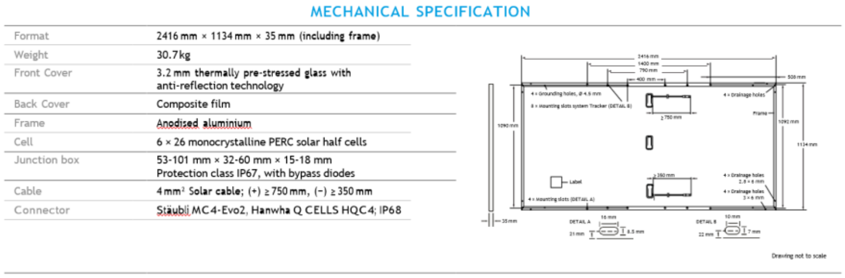
Building Name		**GÜNAM**	**METU Design Factory***	**Transport Management Directorate***	**Mediko (1)**	**Mediko (2)**	**3. Dorm (1)**	**3. Dorm (2)**	**4. Dorm (1)**
Roof Type		F	P	P	F	F	F	F	F
Horizontal	[m]	31.5	8	12	9	23	33	27	33
Vertical	[m]	27.5	50	57	20.5	7.5	5	4	5
Area	[m]	866.25	400	684	184.5	172.5	165	108	165
Azimuth Angle of the Building	[°]	0	-15	90	-15	-15	15	10	5
Azimuth Angle of the Panels	[°]	0	-15	0	75	-15	15	10	5
Tilt Angle of the Panels	[°]	35	36	35	20	36	36	36	35
Number of Panels in Parallel		5	6	2	4	8	5	2	5
Number of Panels in Series		13	10	24	17	9	13	23	13
Total Number of Panels		195	240	192	68	72	65	46	65
Orientation of Panels		P	L	P	P	P	L	P	L
Number of Sub-Arrays		3	4	4	1	1	1	1	1
Number of Inverters *(per sub-array)*		5	6	2	4	8	5	2	5
Inverter Power	[kW]	9	5.5	15	10	5.5	9	15	9
Nominal Power	[kWp]	115	426	339	40.1	42.5	38.4	27.1	38.4
Energy Output	[MWh/yr]	193	627	501	61.1	74.8	65.1	47	65.7
PR	[m]	0.853	0.892	0.891	0.888	0.897	0.869	0.883	0.87

Building Name		**4. Dorm (2)**	**5. Dorm (1)**	**5. Dorm (2)**	**6 . Dorm (1)**	**6 . Dorm (2)**	**7. Dorm (1)**	**7. Dorm (2)**	**8. Dorm**
Roof Type		F	F	F	F	F	F	F	P
Horizontal	[m]	27	33	27	33	27	33	27	55
Vertical	[m]	4	5	4	5	4	5	4	8
Area	[m]	108	165	108	165	108	165	108	440
Azimuth Angle of the Building	[°]	0	20	15	30	25	25	20	-40
Azimuth Angle of the Panels	[°]	0	20	15	30	25	25	20	-40
Tilt Angle of the Panels	[°]	35	36	35	35	35	35	35	20
Number of Panels in Parallel		2	5	2	5	2	5	2	3
Number of Panels in Series		23	13	23	13	23	13	23	23
Total Number of Panels		46	65	46	65	46	65	46	138
Orientation of Panels		P	L	P	L	P	L	P	P
Number of Sub-Arrays		1	1	1	1	1	1	1	2
Number of Inverters *(per sub-array)*		2	5	2	5	2	5	2	3
Inverter Power	[kW]	15	9	15	9	15	9	15	15
Nominal Power	[kWp]	27.1	38.4	27.1	38.4	27.1	38.4	20.2	81.4
Energy Output	[MWh/yr]	47.3	64.7	46.8	63.7	46.2	64.3	46.5	134
PR	[m]	0.884	0.869	0.883	0.868	0.882	0.869	0.883	0.883

Building Name		**9. Dorm**	**Swimming Pool**	**Gym**	**Workshop Directorate ***	**Heat and Water Management Directorate (1)**	**Heat and Water Management Directorate (2)**	**ODTÜ Kent Housings (1)**	**ODTÜ Kent Housings (2)**
Roof Type		P	P	P	P	P	P	P	P
Horizontal	[m]	55	65.5	38	35	8	7	6.5	6.5
Vertical	[m]	4	29	26	7.5	50	25	46	36
Area	[m]	220	1899.5	988	262.5	400	175	299	234
Azimuth Angle of the Building	[°]	0	25	25	0	90	90	-70	-70
Azimuth Angle of the Panels	[°]	0	25	25	0	0	0	-70	-70
Tilt Angle of the Panels	[°]	20	20	20	20	20	20	20	20
Number of Panels in Parallel		3	6	12	3	3	3	5	5
Number of Panels in Series		11	27	14	28	21	20	18	14
Total Number of Panels		66	648	336	168	252	126	90	70
Orientation of Panels		P	P	P	P	P	P	L	L
Number of Sub-Arrays		2	4	2	2	4	2	1	1
Number of Inverters *(per sub-array)*		3	6	12	3	3	3	5	5
Inverter Power	[kW]	9	20	9	20	15	15	10	9
Nominal Power	[kWp]	38.9	382	198	198.2	149	74.3	53.1	41.3
Energy Output	[MWh/yr]	65.2	548	280	287.1	219	105	83.7	63.9
PR	[m]	0.87	0.874	0.861	0.885	0.891	0.892	0.895	0.878

B. Spec Sheets of PV Panel, Optimizers, Inverters and Lithium-Ion Battery System Used in the Study

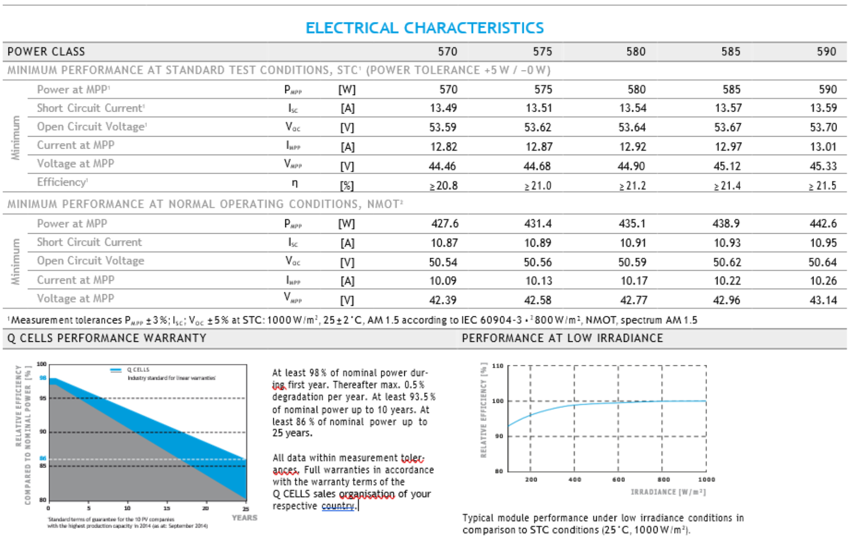
Spec Sheet of Q.PEAK DUO XL-G11.7 570-590 from Hanwha Q Cells



MECHANICAL SPECIFICATION

Format	2416 mm × 1134 mm × 35 mm (including frame)
Weight	30.7 kg
Front Cover	3.2 mm thermally pre-stressed glass with anti-reflection technology
Back Cover	Composite film
Frame	Anodised aluminium
Cell	6 × 26 monocrystalline PERC solar half cells
Junction box	53-101 mm × 32-60 mm × 15-18 mm Protection class IP67, with bypass diodes
Cable	4 mm² Solar cable; (+) ≥ 750 mm, (−) ≥ 350 mm
Connector	Stäubli MC4-Evo2, Hanwha Q CELLS HQC4; IP68

Drawing not to scale



ELECTRICAL CHARACTERISTICS

POWER CLASS				570	575	580	585	590
MINIMUM PERFORMANCE AT STANDARD TEST CONDITIONS, STC[1] (POWER TOLERANCE +5 W / −0 W)								
Minimum	Power at MPP[1]	P_{MPP}	[W]	570	575	580	585	590
	Short Circuit Current[1]	I_{SC}	[A]	13.49	13.51	13.54	13.57	13.59
	Open Circuit Voltage[1]	V_{OC}	[V]	53.59	53.62	53.64	53.67	53.70
	Current at MPP	I_{MPP}	[A]	12.82	12.87	12.92	12.97	13.01
	Voltage at MPP	V_{MPP}	[V]	44.46	44.68	44.90	45.12	45.33
	Efficiency[1]	η	[%]	≥ 20.8	≥ 21.0	≥ 21.2	≥ 21.4	≥ 21.5
MINIMUM PERFORMANCE AT NORMAL OPERATING CONDITIONS, NMOT[2]								
Minimum	Power at MPP	P_{MPP}	[W]	427.6	431.4	435.1	438.9	442.6
	Short Circuit Current	I_{SC}	[A]	10.87	10.89	10.91	10.93	10.95
	Open Circuit Voltage	V_{OC}	[V]	50.54	50.56	50.59	50.62	50.64
	Current at MPP	I_{MPP}	[A]	10.09	10.13	10.17	10.22	10.26
	Voltage at MPP	V_{MPP}	[V]	42.39	42.58	42.77	42.96	43.14

[1] Measurement tolerances P_{MPP} ± 3 %; I_{SC}; V_{OC} ± 5 % at STC: 1000 W/m², 25 ± 2 °C, AM 1.5 according to IEC 60904-3 • [2] 800 W/m², NMOT, spectrum AM 1.5

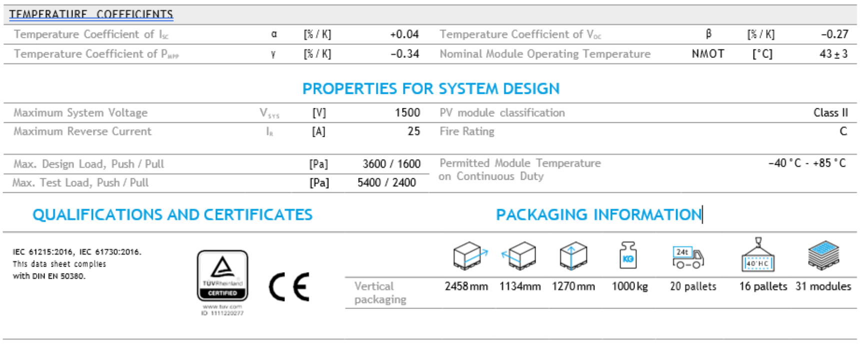
Q CELLS PERFORMANCE WARRANTY

At least 98 % of nominal power during first year. Thereafter max. 0.5 % degradation per year. At least 93.5 % of nominal power up to 10 years. At least 86 % of nominal power up to 25 years.

All data within measurement tolerances. Full warranties in accordance with the warranty terms of the Q CELLS sales organisation of your respective country.

PERFORMANCE AT LOW IRRADIANCE

Typical module performance under low irradiance conditions in comparison to STC conditions (25 °C, 1000 W/m²).



TEMPERATURE COEFFICIENTS

Temperature Coefficient of I_{SC}	α	[% / K]	+0.04	Temperature Coefficient of V_{OC}	β	[% / K]	−0.27
Temperature Coefficient of P_{MPP}	γ	[% / K]	−0.34	Nominal Module Operating Temperature	NMOT	[°C]	43 ± 3

PROPERTIES FOR SYSTEM DESIGN

Maximum System Voltage	V_{SYS}	[V]	1500	PV module classification	Class II
Maximum Reverse Current	I_R	[A]	25	Fire Rating	C
Max. Design Load, Push / Pull		[Pa]	3600 / 1600	Permitted Module Temperature on Continuous Duty	−40 °C - +85 °C
Max. Test Load, Push / Pull		[Pa]	5400 / 2400		

QUALIFICATIONS AND CERTIFICATES

IEC 61215:2016, IEC 61730:2016.
This data sheet complies with DIN EN 50380.

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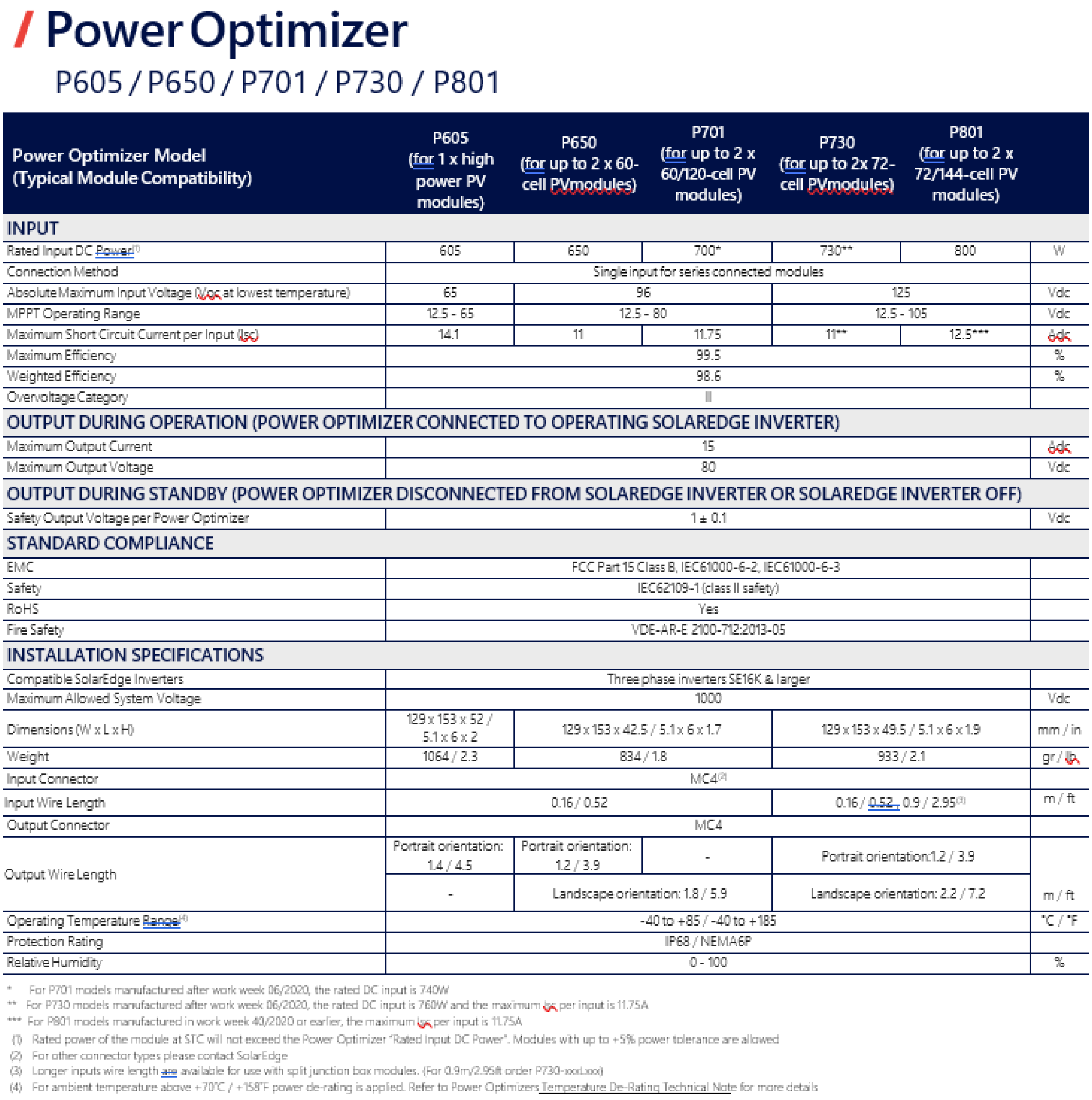
CE

PACKAGING INFORMATION

Vertical packaging	2458 mm	1134mm	1270 mm	1000 kg	20 pallets	16 pallets	31 modules

Spec Sheets of SolarEdge Power Optimizers



/ Power Optimizer

P605 / P650 / P701 / P730 / P801

Power Optimizer Model (Typical Module Compatibility)	P605 (for 1 x high power PV modules)	P650 (for up to 2 x 60-cell PVmodules)	P701 (for up to 2 x 60/120-cell PV modules)	P730 (for up to 2x 72-cell PVmodules)	P801 (for up to 2 x 72/144-cell PV modules)	
INPUT						
Rated Input DC Power[1]	605	650	700*	730**	800	W
Connection Method	Single input for series connected modules					
Absolute Maximum Input Voltage (Voc at lowest temperature)	65	96		125		Vdc
MPPT Operating Range	12.5 - 65	12.5 - 80		12.5 - 105		Vdc
Maximum Short Circuit Current per Input (Isc)	14.1	11	11.75	11**	12.5***	Adc
Maximum Efficiency	99.5					%
Weighted Efficiency	98.6					%
Overvoltage Category	II					
OUTPUT DURING OPERATION (POWER OPTIMIZER CONNECTED TO OPERATING SOLAREDGE INVERTER)						
Maximum Output Current	15					Adc
Maximum Output Voltage	80					Vdc
OUTPUT DURING STANDBY (POWER OPTIMIZER DISCONNECTED FROM SOLAREDGE INVERTER OR SOLAREDGE INVERTER OFF)						
Safety Output Voltage per Power Optimizer	1 ± 0.1					Vdc
STANDARD COMPLIANCE						
EMC	FCC Part 15 Class B, IEC61000-6-2, IEC61000-6-3					
Safety	IEC62109-1 (class II safety)					
RoHS	Yes					
Fire Safety	VDE-AR-E 2100-712:2013-05					
INSTALLATION SPECIFICATIONS						
Compatible SolarEdge Inverters	Three phase inverters SE16K & larger					
Maximum Allowed System Voltage	1000					Vdc
Dimensions (W x L x H)	129 x 153 x 52 / 5.1 x 6 x 2	129 x 153 x 42.5 / 5.1 x 6 x 1.7		129 x 153 x 49.5 / 5.1 x 6 x 1.9		mm / in
Weight	1064 / 2.3	834 / 1.8		933 / 2.1		gr / lb
Input Connector	MC4[2]					
Input Wire Length	0.16 / 0.52			0.16 / 0.52, 0.9 / 2.95[3]		m / ft
Output Connector	MC4					
Output Wire Length	Portrait orientation: 1.4 / 4.5	Portrait orientation: 1.2 / 3.9	-	Portrait orientation:1.2 / 3.9		m / ft
	-	Landscape orientation: 1.8 / 5.9		Landscape orientation: 2.2 / 7.2		
Operating Temperature Range[4]	-40 to +85 / -40 to +185					˚C / ˚F
Protection Rating	IP68 / NEMA6P					
Relative Humidity	0 - 100					%

* For P701 models manufactured after work week 06/2020, the rated DC input is 740W

** For P730 models manufactured after work week 06/2020, the rated DC input is 760W and the maximum Isc per input is 11.75A

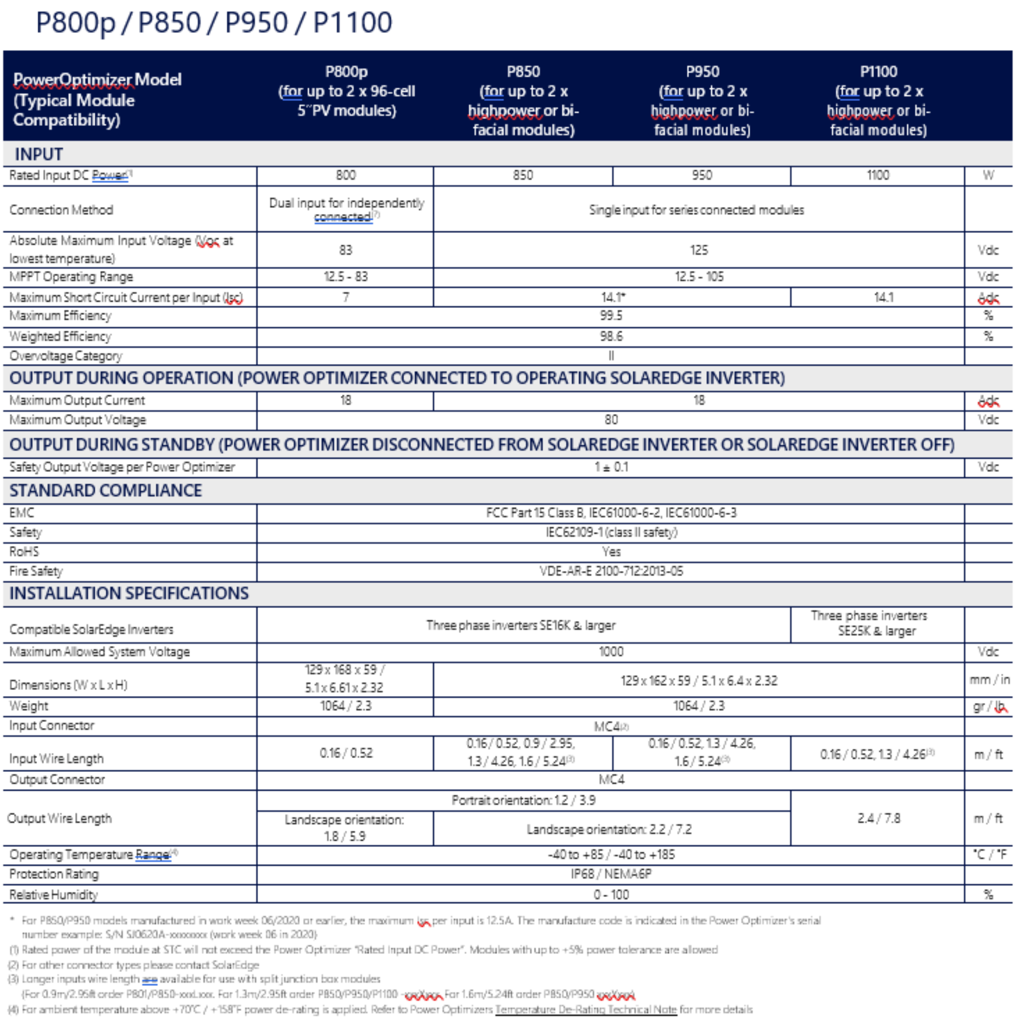
*** For P801 models manufactured in work week 40/2020 or earlier, the maximum Isc per input is 11.75A

(1) Rated power of the module at STC will not exceed the Power Optimizer "Rated Input DC Power". Modules with up to +5% power tolerance are allowed

(2) For other connector types please contact SolarEdge

(3) Longer inputs wire length are available for use with split junction box modules. (For 0.9m/2.95ft order P730-xxxLxxx)

(4) For ambient temperature above +70˚C / +158˚F power de-rating is applied. Refer to Power Optimizers Temperature De-Rating Technical Note for more details



P800p / P850 / P950 / P1100

PowerOptimizer Model (Typical Module Compatibility)	P800p (for up to 2 x 96-cell 5"PV modules)	P850 (for up to 2 x highpower or bi-facial modules)	P950 (for up to 2 x highpower or bi-facial modules)	P1100 (for up to 2 x highpower or bi-facial modules)	
INPUT					
Rated Input DC Power(1)	800	850	950	1100	W
Connection Method	Dual input for independently connected(7)	Single input for series connected modules			
Absolute Maximum Input Voltage (Voc at lowest temperature)	83	125			Vdc
MPPT Operating Range	12.5 - 83	12.5 - 105			Vdc
Maximum Short Circuit Current per Input (Isc)	7	14.1*		14.1	Adc
Maximum Efficiency	99.5				%
Weighted Efficiency	98.6				%
Overvoltage Category	II				
OUTPUT DURING OPERATION (POWER OPTIMIZER CONNECTED TO OPERATING SOLAREDGE INVERTER)					
Maximum Output Current	18	18			Adc
Maximum Output Voltage	80				Vdc
OUTPUT DURING STANDBY (POWER OPTIMIZER DISCONNECTED FROM SOLAREDGE INVERTER OR SOLAREDGE INVERTER OFF)					
Safety Output Voltage per Power Optimizer	1 ± 0.1				Vdc
STANDARD COMPLIANCE					
EMC	FCC Part 15 Class B, IEC61000-6-2, IEC61000-6-3				
Safety	IEC62109-1 (class II safety)				
RoHS	Yes				
Fire Safety	VDE-AR-E 2100-712:2013-05				
INSTALLATION SPECIFICATIONS					
Compatible SolarEdge Inverters	Three phase inverters SE16K & larger			Three phase inverters SE25K & larger	
Maximum Allowed System Voltage	1000				Vdc
Dimensions (W x L x H)	129 x 168 x 59 / 5.1 x 6.61 x 2.32	129 x 162 x 59 / 5.1 x 6.4 x 2.32			mm / in
Weight	1064 / 2.3	1064 / 2.3			gr / lb
Input Connector	MC4(2)				
Input Wire Length	0.16 / 0.52	0.16 / 0.52, 0.9 / 2.95, 1.3 / 4.26, 1.6 / 5.24(3)	0.16 / 0.52, 1.3 / 4.26, 1.6 / 5.24(3)	0.16 / 0.52, 1.3 / 4.26(3)	m / ft
Output Connector	MC4				
Output Wire Length	Portrait orientation: 1.2 / 3.9			2.4 / 7.8	m / ft
	Landscape orientation: 1.8 / 5.9	Landscape orientation: 2.2 / 7.2			
Operating Temperature Range(4)	-40 to +85 / -40 to +185				°C / °F
Protection Rating	IP68 / NEMA6P				
Relative Humidity	0 - 100				%

* For P850/P950 models manufactured in work week 06/2020 or earlier, the maximum Isc per input is 12.5A. The manufacture code is indicated in the Power Optimizer's serial number example: S/N SJ0620A-xxxxxxx (work week 06 in 2020)

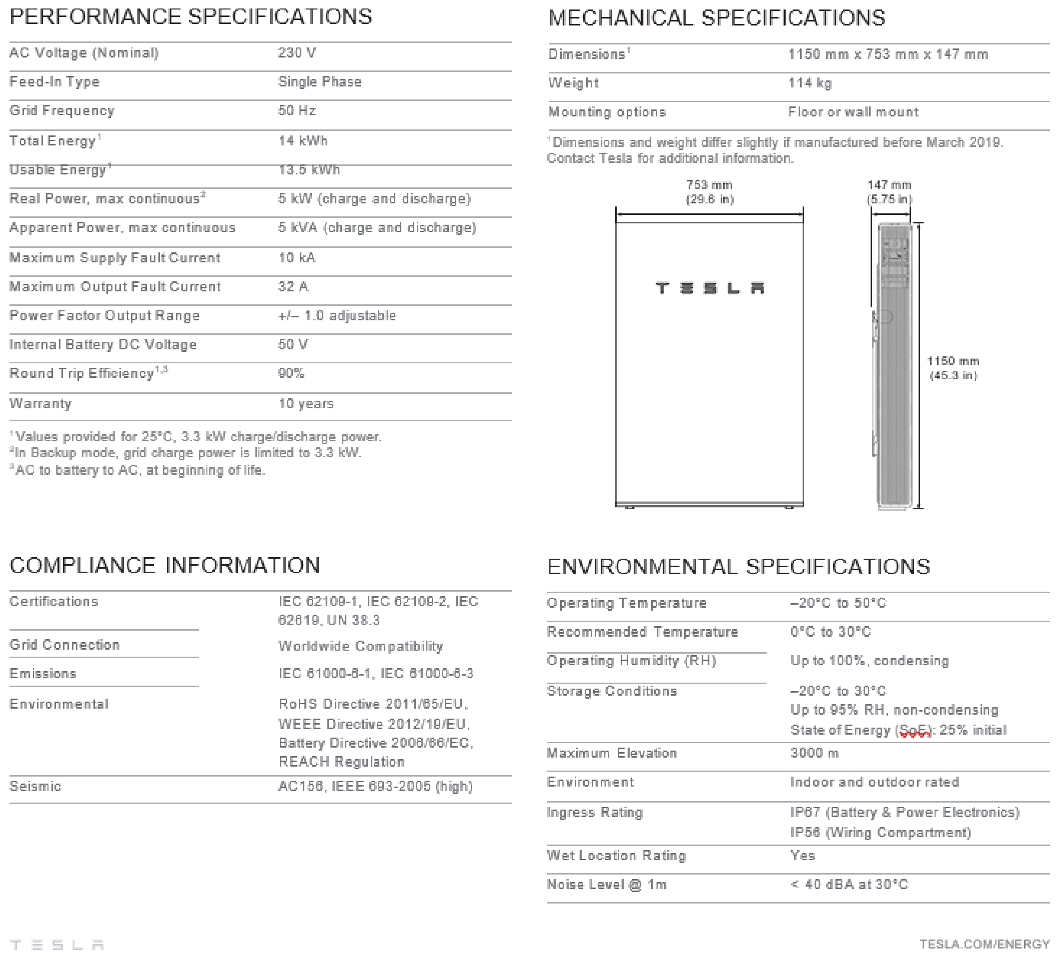
(1) Rated power of the module at STC will not exceed the Power Optimizer "Rated Input DC Power". Modules with up to +5% power tolerance are allowed

(2) For other connector types please contact SolarEdge

(3) Longer inputs wire length are available for use with split junction box modules (For 0.9m/2.95ft order P801/P850-xxxLxxx. For 1.3m/2.95ft order P850/P950/P1100 -xxxXxxx. For 1.6m/5.24ft order P850/P950 xxxXxxx)

(4) For ambient temperature above +70°C / +158°F power de-rating is applied. Refer to Power Optimizers Temperature De-Rating Technical Note for more details

Spec Sheet of Tesla Powerwall 2



PERFORMANCE SPECIFICATIONS

AC Voltage (Nominal)	230 V
Feed-In Type	Single Phase
Grid Frequency	50 Hz
Total Energy[1]	14 kWh
Usable Energy[1]	13.5 kWh
Real Power, max continuous[2]	5 kW (charge and discharge)
Apparent Power, max continuous	5 kVA (charge and discharge)
Maximum Supply Fault Current	10 kA
Maximum Output Fault Current	32 A
Power Factor Output Range	+/– 1.0 adjustable
Internal Battery DC Voltage	50 V
Round Trip Efficiency[1,3]	90%
Warranty	10 years

[1] Values provided for 25°C, 3.3 kW charge/discharge power.
[2] In Backup mode, grid charge power is limited to 3.3 kW.
[3] AC to battery to AC, at beginning of life.

MECHANICAL SPECIFICATIONS

Dimensions[1]	1150 mm x 753 mm x 147 mm
Weight	114 kg
Mounting options	Floor or wall mount

[1] Dimensions and weight differ slightly if manufactured before March 2019. Contact Tesla for additional information.

COMPLIANCE INFORMATION

Certifications	IEC 62109-1, IEC 62109-2, IEC 62619, UN 38.3
Grid Connection	Worldwide Compatibility
Emissions	IEC 61000-6-1, IEC 61000-6-3
Environmental	RoHS Directive 2011/65/EU, WEEE Directive 2012/19/EU, Battery Directive 2006/66/EC, REACH Regulation
Seismic	AC156, IEEE 693-2005 (high)

ENVIRONMENTAL SPECIFICATIONS

Operating Temperature	–20°C to 50°C
Recommended Temperature	0°C to 30°C
Operating Humidity (RH)	Up to 100%, condensing
Storage Conditions	–20°C to 30°C Up to 95% RH, non-condensing State of Energy (SoE): 25% initial
Maximum Elevation	3000 m
Environment	Indoor and outdoor rated
Ingress Rating	IP67 (Battery & Power Electronics) IP56 (Wiring Compartment)
Wet Location Rating	Yes
Noise Level @ 1m	< 40 dBA at 30°C

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