METHODOLOGY TO SIZE LARGE SCALE SOLAR PV INSTALLATIONS FOR INSTITUTIONS WITH UNIDIRECTIONAL METERING

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ABSTRACT

METHODOLOGY TO SIZE LARGE SCALE PV INSTALLATIONS FOR INSTITUTIONS WITH UNIDIRECTIONAL METERING

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Solar photovoltaic (PV) power plants are becoming one of the most widely used renewable sources of energy due to the decreasing cost and increasing efficiency of PV panels. For large levels of PV penetration in the electricity mix of a location, it is very important to cater the demand while considering the metering employed for measuring the electricity demand. However, there is no methodology present in the literature that addresses the electricity demand of a location with the solar resource data with unidirectional metering. This research aims to fill this gap in the literature by developing a novel methodology for designing of a PV system covering the technical, economic and ecological aspects. The methodology is general and can be applied anywhere having similar input data and requirements. The developed methodology is applied to Middle East Technical University Northern Cyprus Campus (METU NCC) and a case study regarding installation of large scale PV at the campus is presented. The results of the proposed PV power plant are obtained after verifying the efficiency of the power plant with the measured data on the solar PV power plant at Serhatköy, North Cyprus. The results indicate that if the objective is to minimize the production of excess electricity, a 600 kW system should be installed at METU NCC and if the objective is to maximize the financial benefits, as 1.8 MW system should be installed. The economic results indicate the payback period of the power plant is around 5 years and the Levelized Cost of Energy (LCOE) is obtained to be around 0.13 USD/kWh and METU NCC can save around 871 MT of CO_2 annually.

Keywords: Solar PV; sizing; university; unidirectional metering

ÖZ

TEK YÖNLÜ METRELEME İLE ENSTİTÜLER İÇİN GENİŞ ÖLÇEKLİ PV KURULUM METODOLOJİSİ

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Güneş fotovoltaik elektrik santralleri, PV panellerinin giderek azalan maliyeti ve artan verimliliğinden ötürü en çok kullanılan yenilenebilir enerji kaynakları arasında yer almaktadır. Bir bölgedeki elektrik hattına geniş çaplı PV işlenirken, elektrik ölçümlerinde kullanılan metrelemekte talebin karşılanması çok önemlidir. Fakat hâlihazırdaki literatürde, tek yönlü metrelemeli solar kaynak datası ile bir konumun elektrik talebine adres yapan bir metot mevcut değildir. Bu araştırmanın amacı, bir PV sistemini teknik, ekonomik ve ekolojik açılardan yeni bir metodoloji ile değerlendirerek literatürdeki bu boşluğu doldurmaktır. Öne sürülen metodoloji geneldir ve benzer giriş data ve gereksinimler dahilinde bu metodoloji her yerde uygulanabilir. Geliştirilen bu metodoloji Orta Doğu Teknik Üniversitesi Kuzey Kıbrıs Kampüsü (ODTÜ KKK)'nde uygulanmış olup, geniş çaplı PV kurulumuna dair örnek çalışma sunulmuştur. Önerilen PV santralinin sonuçları, Serhatköy, KKTC bölgesindeki PV istasyonundan ölçülen bilgilerin değerlendirilmesi ve verimliliğinin doğrulanması ışığında elde edilmiştir. Elde edilen sonuçlara göre, eğer amaç harç fazlası elektrik üretiminin minimize edilmesi ise, ODTÜ KKK'ya 600 kW değerinde bir sistem kurulması; eğer amaç finansal kazanımları maksimum düzeye çıkarmak ise, 1.8 MW değerinde bir sistemin kurulması gerektiğini vurgulamaktadır. Ekonomik sonuçlar, sistemin kendi masrafını 5 yılda karşılayacağı yönünde olmakla beraber, ölçülü enerji maliyeti (LCOE)'nin 0.13 USD/kWh olduğunu ve ODTÜ KKK'nın 871 MT CO_2 salınımını önleyeceğini göstermektedir.

Anahtar Kelimeler: Solar PV; boyutlandırma; ünıversite; tek yönlü metreleme

DEDICATION

To my Beloved Parents, Brothers and Sister.

For their unconditional support, trust and encouragement.

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NOMENCLATURE

$A_{CO_2}(t)$	Amount of CO_2 emitted per hour (kg)
A_N	Nominal design area (m^2)
$A_{RCO_2}(t)$	Reduced amount of CO_2 emitted per hour (kg)
A_S	Area of PV panels with respect to Size Factor (m^2)
C_C	Coincidence Coefficient
C_{EB}	Economic Benefits (USD)
C_{GE}	Cost of Grid Electricity (USD kWh^{-1})
c_I	Capacity of Inverter (kW)
C_{IS}	Cost of Inverter System (USD)
C_{IU}	Cost of Inverter module (USD kW^{-1})
C_{NEB_y}	Yearly Net Economic Benefits (USD)
c_p	Capacity of Power Plant (kW)
C_{PP}	Cost of Power Plant (USD)
C_{PV}	Cost of PV module (USD kW^{-1})
C_{PVS}	Total Cost of PV system (USD)
C_{TGE}	Total Cost of Grid Electricity (USD kWh^{-1})
$D_E(t)$	Electricity Demand at every hour (MWh)
$D'_E(t)$	Normalized demand at every hour
D_{max}	Maximum Electricity Demand during the period used for analysis (MWh)
DNI	Direct Normal Insolation (Wh m^{-2})
$E_{GE}(t)$	Energy generated by the solar PV Power Plant and consumed on the location at every hour (MWh)
E_r	Emission rate of combusting fuel (kg MWh^{-1})
$E_{total}(\mathrm{t})$	Total Electricity Generated in time 't' (MWh)
E_{TP}	Total Energy Produced during lifetime of the PV power plant (kWh)

f	Factor for NPV calculations
f_s	Solar fraction
G_{NOCT}	Insolation at Nominal Operating Cell Temperature (800 Wh m^{-2})
I_{bT}	Beam insolation on a tilted surface (Wh m^{-2})
I_C	Insurance Cost (USD)
I_d	Available diffused insolation on the surface (Wh m^{-2})
I_{dT}	Diffused solar insolation on a tilted surface (Wh m^{-2})
I_{max}	Maximum solar insolation for the selected period for analysis (Wh m^{-2})
I_T	Total solar insolation on a tilted surface (Wh m^{-2})
$I_T(t)$	Solar resource on a tilted surface at every hour (Wh m^{-2})
$I'_T(t)$	Normalized solar insolation at every hour
I'_{TC}	Scaled normalized solar resource coefficient
$LCOE$	Levelized Cost of Energy (USD kWh^{-1})
L_{loc}	Longitude of the location on which resources are to be measured
LLP	Loss of Load Probability
$Load\ (t)$	Total Electricity Load in time 't' (MWh)
$LPS\ (t)$	Loss of Power Supply at time 't'
$LPSP$	Loss of Power Supply Probability
L_{st}	Standard meridian of the local time zone
M_C	Maintenance Cost (USD)
$NOCT$	Nominal Operating Cell Temperature (°C)
NPV	Net Present Value (USD)
$R_D(t)$	Reduced Electricity Demand at every hour (MWh)
S_F	Size Factor
T_a	Ambient Temperature (°C)
TA_{RCO_2}	Total Reduced amount of CO_2 emitted per hour (kg)
T_c	Cell temperature of PV panel (°C)
TE_{GE}	Total Energy Generated using Solar PV power plant and consumed on campus (kWh)
t_{ND}	Nominal design time

T_{ref}	Reference Temperature (°C)
VAT	Value Added Tax (USD kWh^{-1})
y	Number of year (i.e. 1, 2, 3, …)
β	Surface tilt (degrees)
β_{ref}	Factor for efficiency calculations of PV (0.0045 $°C^{-1}$)
δ	Declination angle (radians): The angle between the sun-earth line and equator and a vertical to the equator
$\emptyset$	Latitude of the location
γ	Material property, 0.12 for silicon
γ_s	Solar Azimuth Angle (radians)
η_c	Cell efficiency (%)
η_{cr}	Rated efficiency of PV panel (%)
η_{PV}	Efficiency of PV panel (%)
η_{sys}	Performance ratio of the system (%)
λ_c	Constant, 0.0045 K^{-1}
θ_j	Angle of incidence between the surface normal and incident beam which depend upon other angles which correspond to spatial, temporal and geometric parameters (radians)
θ_Z	Zenith angle, the angle between the vertical line and the line of the sun (radians)
ω	Hour angle, angular hourly displacement of the sun by 15° per hour East or West in a day

CHAPTER 1

INTRODUCTION

1.1. Motivation

Middle East Technical University Northern Cyprus Campus (METU NCC) is a university located in Northern Cyprus on the Mediterranean island of Cyprus. Like on many islands, electricity in Northern Cyprus is relatively expensive and energy costs represent a significant fraction of METU NCC's operating budget. Even though Cyprus has large solar resources, currently almost all of the electricity is generated using fuel oil. METU NCC recently applied for a license to install a 1 MW solar photovoltaic (PV) system to reduce energy costs, to use for research and educational purposes, and to promote campus sustainability. The primary motivation for this thesis is to develop a general methodology to size and analyze the economic, energetic and environmental performance of a PV system for conditions like those at METU NCC, and then apply this methodology to METU NCC as a case study.

1.2. Energy Situation in the World and Northern Cyprus and at METU NCC

The world relies heavily on fossil fuels for energy production and electricity generation. Figure 1.1 shows the current global energy mix of different technologies for electricity generation. The motivation to select thesis on solar PV stems from the concern regarding the increase in greenhouse gas emission levels and METU NCC was selected as case study due to the good solar resources of North Cyprus and the lack of renewable energy technologies in the energy mix of the country. According to the World Energy Outlook, the energy from renewable energy resources will be tripled from 2010 to 2035, reaching 31% of all energy sources. Hydropower would comprise half of the total renewable energy percentage, wind would comprise one-fourth of the total and solar photovoltaic (PV) 7.5%, increasing the utilization of solar energy 26 times from 2010 – 2035 [1].

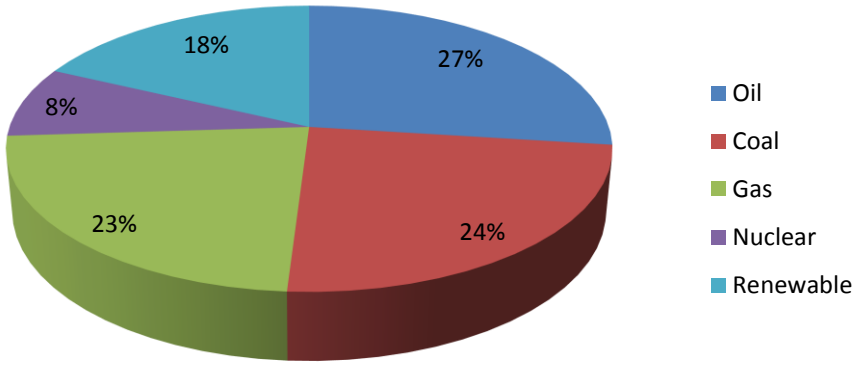


Figure 1.1 Current global energy mix by technology [1]

The climate is becoming more unstable as the greenhouse gas (GHG) emissions are increasing due to the increased use of fossil fuels in industries for power generation. More than half of the GHG emissions consist of CO_2, which is primarily a result of fossil fuel combustion [2]. The use of fossil fuels is of major concern due to two main reasons; one is the GHG emissions and the other is the rapid depletion of the fossil fuels [3]. There is a need to look for clean and renewable energy resources, and there are several options including wind, hydro, biomass, solar and geothermal etc. All these renewable systems are environment friendly and they have negligible amounts of GHG associated with them [4]. The utilization of these potential energy resources is dependent upon a variety of factors; the geographical location, availability of resources, economic factors, etc. Certain regions in the world are abundant in a particular renewable resource, with some having high wind resources, while others have high solar resources and some have the high biomass resources.

Meteorological data indicate that Mediterranean islands tend to have large solar resources. A case study for the Maltese islands reveals that it is totally dependent upon fossil fuels for power generation. According to the EU directive for promotion of the use of energy from renewable energy resources, Malta is required to produce 10% of its energy from renewable resources by 2020. Malta has very little land space available because of its small size, which is 316 km^2. Malta, like other islands in the Mediterranean region, has high solar resource potential. The country receives a daily average insolation of 5.29 kWh m^{-2} and a total annual radiation of 1933 kWh m^{-2}. Due to low availability of land, it is suggested to use offshore PV technology to generate electricity to meet the demand of the country [5].

In another case study [6], the potential for electricity generation from solar energy in 25 countries of the EU and 5 candidate countries was analyzed. The highest potentials for utilizing solar energy for electricity generation in these countries are in Portugal and in the Mediterranean countries including Cyprus, Malta and Italy. The study also indicates that good potential exists in some other countries including most parts of Spain, Croatia, France, Greece, Southern part of Turkey, and Corsica. The research reveals that in the urban residential regions of these countries, annual electricity in the range of 1100 and 1330 kWh per installed kW_p can be generated using a typical PV system [6]. Another study suggested an Energy plan that offers the use of solar systems to minimize the dependency of Sardinia and Cyprus on oil for power production. The Energy plan takes into account the energy requirements for each sector separately. It suggested the use of solar systems for hotels and tourism infrastructure and biomass for agricultural and other purposes [7].

Cyprus is a small island, with a total area of 9251 km^2. It is the third largest island in the northeastern Mediterranean [8]. It is situated at 35°N of Equator and 33°E of Greenwich. Northern Cyprus has a total area of 3354 km^2. Northern Cyprus has a typical Mediterranean climate, with an average temperature of 28°C in summer and around 11°C in winter. There are no oil or gas reserves in the island. The southern part of Cyprus, also known as South Cyprus has good wind potential in some of the regions [9]. North Cyprus, on the other hand has good solar resources but wind resources do not seem to be ample enough to be considered for electricity generation. Right now, North Cyprus is almost completely dependent upon imported oil and petroleum products for energy generation, with just a 1.3 MW PV power plant in the energy mix of the country.

The Cyprus Turkish Electricity Authority (KIB-TEK), a local utility company, which is run by the state, is responsible for generation, transmission and distribution of electricity to all sectors in Northern Cyprus [10]. Due to financial constraints, to generate electricity, KIB-TEK uses heavy fuel oil no.6, which has high sulfur content (3.5% by weight). Utilization of this fuel poses threats to the environment but due to a lack of strict regulations on environment-friendly energy generation systems and financial problems, it is being used. The total power of KIB-TEK and power per station is presented in Table 1.1. The utility company is responsible for the supply of electricity to customers but there is no control over electricity consumption. If the demand rises beyond the supply, the company would have to increase the capacity. Small islands that incorporate renewable energy resources rely mostly on hydro power but Northern

Cyprus has no such reserves. The use of other renewable resources also requires a broad analysis and in-depth studies [10].

Table 1.1 KIB-TEK Power Stations and their capacities

Power Stations	**Power**	**Total Power MW**
Teknecik	2 x 60 MW Steam Turbine	120
Teknecik	2 x 17.5 MW Diesel Generator	35
Teknecik	6 x 17.5 MW Diesel Generator	105
Dikmen	1 x 20 MW Gas Turbine	20
Kalecik	4 x 17.5 MW Diesel Generator	70
Güzelyurt	1.3 MWp Photovoltaic Plant	1.3
	Total Capacity (MW)	351.3

As discussed above, Cyprus is quite rich in solar resources but has a dearth of water resources, so electricity generation from hydropower is not feasible. Additionally, STE (Solar Thermal Electric) systems are generally large; usually greater than 10 MW and in comparison, PV systems are more modular. Moreover, the island is not rich in fossil fuels and electricity generation is dependent upon the use of heavy fuel oil which is imported. Some research has been done to estimate the wind potential of the country and if the country has enough wind potential, then it can be harnessed to generate electricity. Solar resources, on the other hand, are proved to be abundant in the region and it is possible to generate a large amount of electricity using PV technology. The population of Northern Cyprus was approximately 256,644 in 2011 according to the last census [11]. Cyprus has approximately 8 universities enrolling more than 50,000 students [12], which are large numbers for a small country. So a large portion of the population is studying in universities. This suggests that universities contribute to a major portion of electricity consumption in the country and if sustainable university concepts are employed in all universities, it can greatly reduce the demand and consequently the use of fossil fuels.

Middle East Technical University Northern Cyprus Campus (METU NCC) is also dependent upon KIB-TEK for electricity generation. Furthermore, the university has taken various measures to promote sustainability, including taking a green campus initiative and a graduate degree in sustainability. Considering the current electricity source and the good solar radiation received by the university and its measures to promote sustainability, it can be stated that the

university can benefit greatly by the installation of a Solar PV power plant on-campus. Additionally, the university administration has taken keen interest in installing a PV power plant and has already applied for the license of a 1 MW PV power plant. The design of the power plant will be partly based on the key findings from this research. METU NCC has plenty of space for the installation of a new PV power plant. Currently only unidirectional metering is employed at the METU NCC so the proposed PV system is sized based on the economics of unidirectional metering because if the deigned system is too big, it will generate electricity that exceeds the current electricity demand of the campus and the excess electricity generated will be given free to the utility company. This means that to size a PV system, there is a need to analyze both temporal variations in the PV output as well as the electricity demand. If this study proves to be feasible, it may benefit the university in cutting down its expenses on electricity consumption and although not allowed now, in the future may even profit by selling some of the generated power to the grid if a feed-in-tariff is introduced. An additional important factor is that this study may prove to be a pilot project for other universities in the region or globally, and cumulatively this may cause a reduction in greenhouse gases harming the environment.

1.3. Campus Sustainability Programs

Campus sustainability is not a new concept. As discussed earlier in the chapter, the motivation for selecting a study on campus sustainability is a result of the energy conditions of North Cyprus. The reason to select solar PV to contribute to this concept has also been explained in terms of the good solar resources on the island as well as the benefits of utilizing solar PV for electricity generation and lessens the amount of bills paid to the utility company.

Several studies have been performed for achieving campus sustainability. In the housing division of University of Michigan, a sustainable management approach has been presented [13]. The study suggests methods to manage the sustainability of the housing's environmental operational areas. The areas were classified as water and energy, procurement and design, dining, waste, and grounds management. The studies quantified the amount of material being purchased for the housing. It suggested that the materials being purchased for the housing, to a maximum extent, should be biodegradable. The study also emphasizes on the development of a clear vision statement. It also proposed a mission and goal statement for the sustainability management program which encouraged them to reduce the water and energy consumption, and to eradicate the utilization of toxic chemicals [13].

Another study proposed an integrated approach to achieve campus sustainability [14]. The research suggested, as discussed above, to have a clear vision and commitment towards sustainability. The paper suggested the implementation of EMS (Environmental Management System) for universities. It explained that EMS would be beneficial as its certification and implementation would help and drive the universities to assimilate health, safety and environmental management systems. The study emphasizes the need to build green buildings, provide community services, sustainability related trainings and seminars, introduction of sustainability in the curriculum and the promotion of the sustainability concept through continuous research and development [14].

Research regarding the sustainability of Thammasat University Rangsit Campus is performed [15]. The research focuses on the university in terms of energy efficiency and environmental traits. The authors selected 12 buildings in the campus to suggest steps to optimize energy management and energy conservation. The buildings included a dormitory, campus library, sports center, offices, faculty of engineering, bookstore etc. All these buildings were evaluated in terms of energy efficiency and environmental impacts. The results indicated that most of the buildings showed unsatisfactory results. The university was already following a green university approach so the planning and architecture work was satisfactory as the green areas and landscapes were conserved. The authors suggest energy conservation concepts for the design of new buildings or maintenance of the existing infrastructure. The authors also suggested the use of energy saving electrical appliances and replacement of air conditioning system after 10 years of usage. Additionally the research proposed the use of solar energy on the building rooftops to provide alternate energy resources [15].

1.4. Solar Photovoltaic Systems

The photovoltaic (PV) industry is among the most rapidly developing industries. The PV production rate increased by 60% between the year 2003 and 2004 and by 44% between 2004 and 2005. It has achieved a steady growth rate of 40% over the past few years [16]. Additionally, the global PV installed capacity increased by around 44% between 2011-2012 [17] . The installed capacity of PV is increasing globally and will continue to increase. At the end of 2009, it was a total of 24 GW and after 2010, it became 71.1 GW globally and by the end of 2012, the figure reached a value of above 100 GW [17]. In future, the introduction of large PV systems to produce electricity would even prevent the investment in existing grid extension

or a new conventional plant [4]. PV is not commonly used to generate electricity and the use is quite negligible compared to conventional methods for power generation. The reason for less utilization of PV are the high costs associated with the technology and fairly less market experience [2]. Even though if a country has sufficient solar energy resource potential, it may still not invest in PV due to the high cost. Research is being done in this area and efforts are being done to bring down the cost of PV technology; it is decreasing rapidly with time and it may become cheap enough to compete with energy generation via fossil fuels. A large number of companies are actively participating in bringing down the cost of production of PV panels, through planning and experience [18]. According to a research performed by [3], The United States department of energy has defined its objective to reduce the cost of electricity produced by solar technology to 6 US¢ kWh^{-1} by the year 2020.

A typical PV system consists of PV panels, inverters, and Balance of System (BOS). The Balance of System includes the wiring; power conditioning equipment, mounting and cabling [19]. The system also includes the permitting, inspection and installation costs which are also referred to as soft costs [20]. The efficiency of electricity being generated using PV panels is dependent upon the efficiency of the PV cells being used and the efficiencies of equipment that are needed with the PV panels to produce electricity. Weather conditions also play a big role in the efficiency of PV systems. As the cell temperature of the PV panel increases with ambient conditions, its efficiency goes down [21]. Additionally, even if efficiency is constant, the annual output varies with variation in solar resources due to climatic conditions. The efficiencies of monocrystalline silicon, polycrystalline silicon and amorphous silicon solar cells are approximately 15%, 12% and 5% respectively. The efficiency of cadmium telluride (CdTe) and CIS (Copper-Indium-Diselenide, $CuInSe_2$) is around 8% [18]. This suggests that the overall efficiency of a solar PV power plant may not be as high as power plants using conventional resources. So research is being done to increase the efficiency of the systems while keeping the cost low and it is one of the major scientific challenges of the 21st century.

Numerous studies have been done to suggest the feasibility of building PV farms or power plants for the generation of electricity. Saudi Arabia, which is rich in oil and gas reserves, is also looking for alternate ways to produce electricity to meet the demand of the country. The country has a total electricity generation capacity of 35 GW and it is suggested to increase the capacity by 72 GW by 2022. The country has a high potential of solar resources and it is suggested to use PV power plants to increase the capacity. The cost of electricity for PV power

plants in Saudi Arabia were estimated to be between 0.216 USD kWh^{-1} and 0.24 USD kWh^{-1} [22].

There are several methods present in literature that are used to design either standalone or grid-tied systems. The use of statistical tools for sizing of standalone PV systems is quite commonly found in the literature. For a standalone system to be constructed, the reliability of power supply is a major concern. Some of the researchers have used the concept of the reliability of power supply by using the concept that reliability is quantified in terms of the time during which uninterrupted supply is provided by the PV system, in contrast with Loss of Load Probability, LLP to perform the sizing of PV system [23] [24] [25]. To construct the sizing curve of a PV system based on LLP, modeling of PV system operation for considerable periods of time is required [23]. Sizing curve of standalone PV system specifies the generator ratings and battery capacities to meet a specific load pattern [26]. Such methods require time series of solar radiation to be produced synthetically by the use of an algorithm based on solar radiation indicators. The authors in [23] suggest a new method to size a PV system which takes solar radiation data as an input and offers advantage over the LLP approach by eliminating the need to produce synthetic time series of radiation data. The methodology followed is based on analyzing the PV system operation as a function of time by using it as a series of climatic cycles and a PV system near London, UK is sized by using 10 years of measured daily solar radiation data to exemplify the methodology [23]

Researchers in [24] have focused on suggesting the use of daily radiation data series as input to size a standalone PV system; in comparison with monthly average values with the system configurations more appropriate to handle unpredictable situations. The authors have used two methodologies to achieve their motive; first is the examination and derivation of the sizing curves for three different locations: London weather station (UK), Salzburg airport (Austria) and Heraklion (Greece). The second methodology is the scrutiny of long-term storage requirement for two different locations: Efford (UK) and Potsdam (Germany).

Kaushika, N. D. et. al [27] proposed a simulation model for the sizing of standalone solar PV Systems with interconnected arrays. The method used the Loss of Power Supply Probability, $LPSP$, to predict the risk of not satisfying the load demand and hence used $LPSP$ as parameter for sizing. $LPSP$ for a day was defined as the ratio of loss of power supply values for 24 h to the sum of load demanded for 24 h.

$$LPS(t) = Load(t) - E_{total}(\mathrm{t}) \tag{1}$$

$$LPSP = \frac{\sum_{t=1}^{t=24} LPS(t)}{\sum_{t=1}^{t=24} Load(t)} \tag{2}$$

In this study the non-tracking and single-axis tracking aperture arrays having cross-connected modules of single-crystalline silicon solar cells in a (6 x 6) modular configuration were considered. The simulation results were shown using an example where load demand, $Load(t)$ was assumed to follow uniform probabilistic distribution whereas the global solar radiation data was generated by an algorithm which was based upon concept of fuzzy random variable representation of cloudiness index. A linear programming approach with the objective to minimize the Loss of Power Supply was constructed with the number of modules and number of batteries as decision variables. This LPS was used to obtain the $LPSP$. The authors presented the number of Solar PV modules and batteries corresponding to zero values of $LPSP$ on diurnal basis during the year round cycle of operation for a given year. The results indicated that the optimum requirement of modules and batteries are noticeably different for systems with fixed and tilted aperture and the single-axis tracking aperture arrays [27].

Posadillo, R. et. al [28] used a sizing method for standalone PV installations with variable monthly demand and variable monthly panel tilt, based on concept of Loss of Load Probability, LLP, a parameter that is used to characterize system design. Loss of load probability for a month was defined as

$$LLP_j = \frac{\int_t energy\ deficit}{\int_t energy\ demand} \tag{3}$$

The method included information on the standard deviation of loss of load probability and on two new parameters : annual number of system failures (f) and standard deviation of annual number of failures as reliability parameters. The method used the daily irradiation data, monthly averaged daily demand data to find the Generator capacity and storage capacity, which were used to calculate the LLP and failures for a selected size of the system. An iterative procedure was suggested to find LLP for different sizes which lead to correct decision making about the size as per requirements of reliability. The authors applied this methodology for Cordoba, Spain

[29]. The results from the study indicate that for low values of number of modules, the *LLP* is linearly related to the number of modules, regardless of storage capacity. The method explained by the researchers enables the decision makers observe the number of expected failures in the installation according to the number of modules and number of cells.

For grid-tied systems, there are also different approaches present to size the PV system. The researchers in [30] determined optimal PV/inverter sizing ratios in selected European locations for grid connected PV systems. The methodology used was based on three different sizing methods; first the energetic sizing ratio, which quantified the energetic performance of the PV system as a ratio of annual energy output of the inverter to the rated power of the PV system. The second methodology was based upon the economic feasibility of the system which was calculated as the ratio of annual output of energy from the inverter to the sum of the products of rated PV power capacity and its cost with the BOS and the rated inverter capacity and inverter cost. The third methodology was dependent upon the determination of annual energy output per annualized investment cost. The results from the research were translated in terms of total system output, system output per specific cost of system, system output per annual specific cost, PV surface orientation and inclination, tracking system, characteristics of inverter, insolation and PV/inverter cost ratio. For low efficiency inverters for sizing ratios of 1.5, 1.8 and 1.3, and for medium efficiency inverter with sizing ratios of 1.4, 1.5, and 1.2 maximum total output was presented for horizontal, vertical and 45^{o} inclined surface in their paper. They found that there is significant impact on optimum PV/inverter sizing ratio of PV/inverter cost ratios and PV and inverter lifetime. Their results show that PV/inverter sizing ratio had less impact on PV array performance when cost of PV array was higher than cost of inverter [30].

The researchers in [31] used a new modeling approach and defined a new objective function for modeling optimal sizing of PV irrigation water pumping system. They considered and analyzed various system elements and characteristics like: local climate, soil, crops, irrigation method and PV water pumping systems. They presented a new mathematical hybrid optimization model for optimal PV sizing of irrigation water pumping system. They defined constraints in simulation model and used dynamic programming for optimization. Their model was successfully tested on two different locations in Croatia and the results showed that optimal nominal power of PV generator obtained from this method was relatively smaller than that found using common method of sizing [31].

The researchers in [32] considered PV module technology, PV orientation and inclination, type of inverter and location to formulate and apply an optimal sizing methodology for grid connected PV systems. Various locations in Bulgaria and Corsica (France) were used to apply this method with the results indicating that inverter efficiency curve was the main parameter affecting the sizing. The results also showed that there was not enough influence of PV module technology on sizing, but for amorphous PV modules the case was different and special remarks are present in the research work. Another noteworthy observation found in the paper was that performance was affected by the inclination of PV systems, specifically when the inverter had less power capacity as compared to PV peak power [32].

The study performed by [33] was focused on precise and accurate measurement of solar radiation intensity for accurate and reliable system sizing. The authors examined the variations in power output of a PV pumping system as a result of using some solar radiation correlations. Comparing the results with those of long-term solar radiation measurements, it was found that the system sizing with the measurements and with the most appropriate correlation, were significantly different from each other. That was because of the predicting errors in solar radiation data, which were nonlinearly propagated to the power output of the system [33].

As discussed, there are different sizing methods are present in the literature to design PV systems. Some of the methodologies present for sizing the system depend upon probabilities and probabilistic function. There exists no methodology in the literature that directly addresses the hourly electricity demand for a specific location to size a PV system. Additionally, all of the methodologies discussed above are either using measured solar resource data or simulated solar resource data but none of the methodologies discussed utilized actual hourly electricity demand data with the hourly solar resources to size the PV system based on unidirectional energy metering.

A feasibility analysis for PV at METU NCC has also been performed earlier [34]. The results indicate that a grid-tied PV power plant to meet the needs of the campus proves to be cheaper than the current supplier of electricity. The cost of electricity using the grid-tied system was 0.13 USD kWh^{-1} and the cost of electricity generation using the conventional system was around 0.18 USD kWh^{-1} without externalities and 0.195 USD kWh^{-1} considering externalities. The cost of generating electricity using a standalone PV power plant with batteries for storage was around 1.8 times higher than grid-connected PV system and was approximately 0.24 USD

kWh^{-1}. The break even time for grid-tied PV power plant of 6 years was also found to be less than the life expectancy of the power plant of 20 years [34].

The feasibility analysis performed for METU NCC earlier [34], did not contain any energetic model to estimate the PV module efficiency with varying ambient conditions. Additionally, the study did not include any analysis regarding the variation in orientation of the system. The combustion equation used to estimate the reduction in CO_2 utilizes the use of an empirical formula for the heavy fuel oil no. 6. It can be argued that the empirical formula used can only estimate the minimum amount of CO_2 generated. However, the heavy fuel oils range between $C_{10} - C_{50}$ [35], so the actual amount of CO_2 produced cannot be calculated unless the molecular formula is known. Lastly, the research for a PV power plant at METU NCC did not contain the study of renewable policies for the country.

1.5. Uncertainties in the measured solar resource data at METU NCC

While observing the measured solar resource data at METU NCC, it was observed that the data had some outliers and points that did not look correct. For instance, some data points showed no global horizontal solar insolation but showed solar resources otherwise. Additionally, few data points yielded negative diffuse insolation, which is also incorrect. The solar resources at METU NCC after September 24 seem to show higher values suddenly, which also seems incorrect. In addition to that, April 2014 showed quite low solar resources and May 2014 seemed very less compared to June 2013. Due to the observed uncertainties in the measured solar resource data, it was essential to compare the METU NCC solar resource data with some other valid data for reference. Two data sets were thus obtained to compare the METU NCC data against them. One was synthetic TMY2 (Typical Meteorological Year) and other was obtained from the website of existing PV power plant at Serhatköy, North Cyprus.

1.6. Objectives

As discussed earlier regarding the population in the universities in North Cyprus and the good solar resources in the island, if the universities utilize solar resources to generate electricity, they can add to much load reduction and consequently reduce the dependency on fossil fuels. Selecting PV systems to generate electricity seems to be the best option for universities including Middle East Technical University Northern Cyprus Campus (METU NCC). This

became the motivation to develop a methodology based on the available solar resource data, which includes the electricity demand data to propose the design of a PV system for a specific location.

The objective for this work is to develop a methodology that is general and can be used for any location of the world, depending upon the availability of the input data used and apply it as an example to determine the limits to large scale PV penetration at METU NCC by analyzing the temporal coincidence of electricity generation and demand considering that currently METU NCC cannot be paid for or receive any credit for electricity fed to the grid. The case study thus performed by using the methodology builds directly on the work performed earlier [34], such that:

- Monthly demand data of the campus was used before and this research is based on the hourly electricity consumption data for the campus;
- Monthly solar resource data of the campus was utilized earlier but for this work, the hourly solar PV output models are developed
- A horizontal panel was considered earlier while in this work, tilted panels are considered to maximize the solar resource output

As discussed in Section 1.5, it was important to compare the measured METU NCC solar resource data set, both in terms of investigating how much the incorrect data affected the sizing and design of the system and also to what extent synthetic TMY2 data or some other validated data can be substituted to replace the bad and incorrect data measured. So comparing the two data sets is also one of the main objectives of this research.

1.7. Overview of the thesis

Based on the lack of a methodology to size and analyze PV systems that is based on hourly electricity demand and solar resources with unidirectional metering and the certain gaps mentioned in the research conducted for METU NCC, the objective for this research is to present a clear methodology for designing PV systems based on the temporal variations in the electricity demand and the PV output. Chapter 2 provides the details regarding the methodology. A temporal coincidence methodology is developed to analyze the electricity demand profiles and the solar resource data to size the PV system in a way that there are a

minimum number of hours in a year in which the supply of electricity from the PV system exceeds the electricity demand of the campus. Furthermore, this research also incorporates the use of an energetic model to predict the efficiency and the actual output of the PV panels considering the ambient conditions. The model is also verified from data obtained from the solar PV power plant at Serhatköy, North Cyprus. This research also provides an economic model for the economic analysis regarding the design of a PV system. Furthermore, this research also uses the emission rates obtained from the EPA website to accurately predict the amount CO_2 emissions avoided by installing a PV power plant. The system size is further explored through different parametric studies for METU NCC which are explained in detail in Chapter 4. Lastly, this research also presents an overview of the energy policies in North Cyprus. The methodology presented is general and the models used are applicable to other locations considering similar projects. The data used for the study contains the hourly electricity demand of the campus for a period of 1 year, from 1st June, 2013 to 31st May, 2014. In addition to that, it also contains the hourly solar resources for the same period which are used for the analysis. The study also includes the best orientation to maximize the electricity output of the PV panels. The case study presented is focused primarily towards the determination of the largest PV capacity that would not feed significant electricity to the grid; i.e., the PV output rarely exceeds the electricity demand of the campus.

CHAPTER 2

ENERGY POLICY REVIEW FOR THE ISLAND OF CYPRUS AND NORTHERN CYPRUS

This chapter presents an energy policy review for Cyprus and then sheds light on the energy policy for North Cyprus. The objective of this chapter is to present an overview regarding the pertaining energy policies for North Cyprus and due to the lack of literature available for energy policies for North Cyprus, the energy policies of Cyprus are also addressed. The island of Cyprus is basically the 3rd largest island in the Mediterranean region and it is a member of the EU. It was divided into Northern and Southern parts in the year 1974 when the Turkish army claimed the Northern part. It is commonly known as Turkish Republic of North Cyprus (TRNC). Currently, there are approximately thirty thousand Turkish military personnel deployed in TRNC [36]. The Southern part is controlled by Greece. The two parts are separated by the ceasefire line known as Green Line, which is looked after by the United Nations. Nicosia, the capital of Cyprus, is the largest divided capital in the Europe. The Southern two third population of the island are Greek Cypriots while one Northern one third population are Turkish Cypriots [37].

The renewable energy policy of Cyprus shoots from the obligations set by the European Union (EU) and the agreement with Kyoto Protocol. European Commission has set growth targets for its member countries for the use of Renewable Energy Sources (RES). For this purpose White paper for renewables is the first step to be considered a milestone. The research performed by [8][38] in the year 2007, formulated a renewable energy strategy for the EU. Cyprus being a member of the commission must meet a target of 6% electricity production from RES and increase the contribution further to 12%. In order to achieve the set target, Action Plan for Renewable Energy Sources in Cyprus was formulated in 2002. Under this scheme, the maximum size of the PV systems subsidized by the electricity authority was 5 kW and the produced electricity was brought at a cost of around 0.27 USD kWh^{-1} [8].

The energy policy traits have become more important in the EU due to the price instability and the interruption in the gas supply from Russia to Europe. Furthermore, the increased emissions of CO_2 in the emissions leading to global warming is also affecting the long-term energy

strategies and enhancing the need to include RES in the energy mix. The estimated national electricity consumption was expected to reach 5000 GWh by 2010, mandating approximately 300 GWh production by RES in order to achieve the national target of obtaining 6% of the total energy from RES. Furthermore, to encourage the utilization of RES in Cyprus, a National Fund was created to provide the required assistance and feed-in tariffs [39]. However, by 2010, renewables and other energy sources only comprised 1.8% of the total electricity generation in Cyprus [40].

Since Cyprus has set objectives to reduce the dependency on fossil fuels, in a research performed by [41], it was suggested that Cyprus should reduce the energy consumption and promote the use of renewable energy resources and a law was passed in Cyprus in 2003 for promoting the use of RES and lessening the energy consumption. The contribution of RES in total energy consumption of Cyprus was expected to increase from 3.5% in the year 1995 to 9% in 2010. In 2005, 1% of the total fuels used in transportation were expected to be replaced by biofuels. However, still by 2007, the use of biofuels still remained 0% [41].

If the small shares of electricity produced by utilization hydro and biomass resources are excluded, Cyprus will have to start from zero to achieve the target of 6% electricity from RES. Due to relatively high costs of PV systems, applications of such systems are limited. Cyprus receives higher amounts of solar irradiation and therefore it can be anticipated to have a greater share of PV systems in Cyprus once the technology becomes mature and economically feasible. By 2008, the largest PV application in Cyprus was an 80 kW PV shading system installed at the headquarters of electricity authority of Cyprus. The situation is now changing for PV systems after the implementation of renewable energy subsidization scheme under which 55% of the initial PV installations are subsidized and the electricity authority purchases the electricity from these systems at a price of 0.27 USD kWh^{-1} which is about double the selling price currently [8].

The republic of Cyprus energy forecast model was presented by [42] to help the national authorities to create an excellent and energy efficient action plan for future purposes with respect to the country energy requirements. The model was formed with the help of macroeconomic and energy price assumptions from the combination of data and reports available from official sources. The energy consumption of each main sector was calculated in order to see how this consumption was distributed among diverse fuels. From the official

reports, it was predicted that renewable energy sources will contribute up to 16% by the end of 2010. The energy efficiency of the buildings was forecasted to be on the order of 14% by the year 2020 if natural gas was excluded from the energy policy plan of the Cyprus. It was suggested that the energy efficiency of the whole system can be further improved if Cyprus energy system is focused on road transport as well. Additionally, it was suggested that in order to achieve ambitious targets set as per the European Union directives, the national authorities should give subsidies to renewable energy projects in the residential and domestic sector, which was not the case when the study was performed in 2011 [42].

Cyprus manufactures Solar Water Heaters (SWH) itself as and for every 3.5 persons i.e. for every Cypriot family on average, there is a SWH installed. Local market is also capable of providing PV frames. First PV plant of 3 MW became operational in 2008-2009 and several other studies and research is being conducted to make PV projects feasible. No clear policy had been given from the TRNC government by the year 2006 over the stance of integrating renewable energy into the grid. It was suggested that Northern Cyprus having similar resources could easily fulfill its needs through RES especially solar energy by following the European Union code of conduct [8].

In a research performed by [43], the role of solar water heating industry in the energy scenario of Cyprus was presented. The research revealed that Cyprus can fulfill 6.5 % of its total energy needs from the solar energy by presenting an energy scenario of the country. The main problems identified for solar water heating industry were mainly arising from materials and production, design, installation, operation, maintenance and environment considerations. The study also discussed the installation of a 50 MW solar-thermal electric power generation system as a positive step taken by the government of Cyprus [43].

The past 20 years trend of the Northern Cyprus shows that the average annual energy consumption increase is 7.1% and average annual peak demand remains 5.5% respectively. The solar heating is the best example of alternative energy sources deployed in Northern Cyprus which is saving at least 72 GWh energy per annum and is also responsible for significant reduction in CO_2 emissions in the atmosphere. As discussed in Chapter 1, currently Northern Cyprus energy mix is almost dependent upon oil and gas despite having no reserves of fossil fuels. As Cyprus is a small island and is separated in terms of grid from the rest of the world therefore promoting alternative energy technologies would be a great success in terms of clean

energy sources for this region and therefore profitability analysis method is demonstrated in the research performed by [10] to find the profitability of a residential 2 kW rated PV system and 10 kW wind electric conversion systems. Another important factor considered in the research were the environmental benefits that may be harnessed by deploying renewable energy sources in the country. It was also concluded that promoting gas water heating and replacing electric water heaters with solar water heaters could reduce peak power demand for heating by 25 MW. Furthermore, installation of 2000 units of 3 kW capacity PV systems in Northern Cyprus would cut down its peak demand of electricity by 6 MW which is sustainable in terms of electricity demand and clean environment.

The research performed by [44] also proposed the utilization of renewable energy resources for providing electricity for Northern Cyprus. The study suggested and presented a model for a dual energy unit in the country which utilized the solar and wind energy. The model was suggested to be applied to all residential locations in the country. The study also focused on the installation of wind power plants in areas with good wind potential, along with the utilization of solar energy to generate steam through a boiler and produce electricity [44].

The TRNC Renewable Energy Commission passed regulations in 2011, which were finalized in 2014. The regulations allow the residential customers to connect RES such as Wind turbines, PV systems, biomass systems etc. to the utility grid by implementing net-metering for systems having capacity up to 5 kW for single phase systems and up to 10 kW for three phase systems. In addition to that, the regulations passed also allow institutions and universities such as METU NCC to connect PV systems with a 10 MW total limit for all institutions throughout TRNC but with unidirectional metering and without net metering or a feed-in-tariff; i.e., if the PV system or any other RES connected to the university in consideration, ever produced more electricity than the electricity demand of the university, the excess electricity would be fed to the utility grid for free. There are considerations for tethering the electricity grid in TRNC to the electricity grid in Turkey through an underwater tie-line, which would benefit TRNC by decreasing the cost of electricity, providing stability to the grid, and enabling a larger penetration of PV in the energy mix of the country. The TRNC Energy Commission seems concerned in allowing larger PV penetration but without any risk that threatens the stability of the electricity grid [45].

This study regarding the feasibility of a solar PV power plant at METU NCC has shown some positive results and the installation of an on-campus solar PV power plant will economically benefit the university, lessen the climatic change by reducing the greenhouse gas emission levels and it may also motivate the rest of the universities in North Cyprus to go green and achieve campus sustainability. As discussed earlier, recently the government of North Cyprus has issued some licenses for electricity generation through renewable energy resources and the acquiring of 1 MW license for METU NCC will also be a positive step forward. It is suggested that North Cyprus, having ample solar resources, should invest more in electricity generation through solar PV and the government should certain measures to lessen the use of fuel oil for electricity generation in the country.

CHAPTER 3

METHODOLOGY

This chapter presents a complete methodology for the design of a PV power plant based on temporal variations in the hourly electricity demand and the PV system output with unidirectional metering covering the technical, economic as well as ecological aspects. The chapter initiates with a methodology for acquiring the electricity demand data followed by a methodology used to clean the demand data for sizing of the system and analysis. The chapter proceeds by providing the methodology used to obtain the solar resource data and the steps used to condition the data according to the need of this research. The methodology used for obtaining the solar resource data and molding it according to the requirement of the research is followed by a Solar Resource Model to estimate the solar resources on any characteristic surface (North, South, East, West, Horizontal and Tilted) for any location of the year at any hour of the day.

After the Solar Resource Model, an Energetic Model for PV is presented which is used to calculate the efficiency of PV panels with respect to varying ambient conditions (temperature and irradiation) whose details are presented in the chapter. The Energetic Model is followed by a novel model to size the PV panels according to the electricity demand of the location in a way that on minimum instances, the electricity being generated exceeds the electricity demand of the location. The mathematical model used for sizing of the PV panels and system is followed by an Economic model to calculate the cost of the PV system and the economic benefits that it will yield for the location. The last model presented in this chapter is an environmental model associated with the potential reduction in carbon dioxide (CO_2) emissions if the PV system is installed. While this methodology is general and therefore can be applied to any location, to communicate the methodology and its significance more clearly, it is introduced through its application to METU NCC.

3.1. Data Acquisition and Handling

3.1.1. Electricity Demand Model

For METU NCC, the hourly demand model is based on measured electricity demand data of the campus obtained from the utility company KIB-TEK. KIB-TEK uses Supervisory Control and

Data Acquisition (SCADA) system to log the electricity demand patterns of the customers and the data obtained for the campus is also from the utility company's SCADA system. The average electricity consumption data of the campus at every half hour of the day were collected and then averaged at every hour to find the total electricity demand per hour of the campus. The analysis presented in this research covers a time span of 1 year from 1st June, 2013 to 31st May, 2014.

3.1.2. Electricity Demand Data Handling

The electricity demand data collected had some data points that were representing very low or constant electricity demand, indicating likely problems with the data. The data are cleaned in two a step process to produce Demand Analysis and Demand Sizing Data Sets. In the first step the Demand Analysis Data Set is produced as follows:

1) The data points having very low electricity demand or constant are identified by plotting the electricity demand with respect to time and observing the points with constant, zero or very low electricity demand. Very low electricity demand is referred to as being less than 15-20% of the electricity demand at the same time on the previous day
2) Data were back-filled by assuming the following:
    a) If the data is for a weekday, the electricity demand at the time with zero demand or very low demand was assumed to be the same as the previous day at the same time
    b) If the data is for a weekend, the electricity demand at the time with zero demand or very low demand was assumed to be the same as the previous weekend
3) The process was followed until all the data are cleaned

Overproduction is defined as the PV system producing more electricity than the campus consumes, and ideally the PV system is nominally designed to be as large as possible while avoiding overproduction. Significantly, during blackouts the measured demand goes to zero, and to avoid overproduction suggests the PV capacity should also go to zero, which is not meaningful. To avoid nominally sizing the PV system based on times of low or no measured demand, the Demand Analysis Data Set is further cleaned to eliminate times of low demand to produce the Demand Sizing Data Set as follows:

1) The average of the Demand Analysis Data Set is found.
2) Standard deviation of the Demand Analysis Data Set is calculated
3) A new term E_{min} is introduced which is the difference between the calculated average and the standard deviation
4) The data points having the value less than E_{min} are eliminated and not used for sizing the PV system
5) The sizing of the panels is done as explained in Section 3.2.3.

The electricity data, after following the methodology described above, was used to perform the relevant analyses.

To more clearly communicate this data cleaning method, the application of this method to METU NCC's demand data is presented. Four characteristic plots for METU NCC's electricity demand are shown from Figure 3.1 to Figure 3.4. Figure 3.1 represents the electricity demand of METU NCC from 11th June 2013 to 17th June 2013 without cleaning the data. It can be seen clearly from the plot that electricity demand around the evening of 11th of June falls rapidly to zero and it also stays constant from late evening of 15th June 2013 till the midday of 17th June 2013. Figure 3.2 represents the electricity demand data for the same time period with cleaned data. It can be seen clearly that the utilization of cleaned data will yield much better results while analyzing the system performance. Furthermore, it can also be observed that the electricity demand for 15th and 16th of June 2013 is lower than rest of the week, which is due to the fact that both the days are weekends and since the academic and administrative buildings in the campus are closed on weekends.

3.1.3. Comparison of Electricity Demand Data

The electricity demand data of METU NCC, obtained from KIB-TEK was also compared with the monthly electricity billing data of the university for the entire year. Table 3.1 presents the results from the comparison. It can be observed that there is some difference in the data obtained from SCADA and from the electricity bills of the university. The difference is a maximum of around 29% in May 2014 and a minimum of 0.87% in the month of June 2013. The annual difference between the two data is 11.4% which is acceptable since the electricity demand data were backfilled and cleaned due to errors in the data.

Table 3.1 Comparison of Electricity Demand Data of METU NCC from SCADA and monthly electricity bills of the university

Month	Billing kWh	SCADA kWh	Difference %
Jun-13	817,840	825,022	0.87%
Jul-13	719,676	881,242	18.33%
Aug-13	675,880	695,230	2.78%
Sep-13	822,400	945,363	13.01%
Oct-13	600,600	749,252	19.84%
Nov-13	547,640	666,316	17.81%
Dec-13	695,600	771,610	9.85%
Jan-14	695,680	653,384	-6.47%
Feb-14	442,360	482,154	8.25%
Mar-14	506,320	571,339	11.38%
Apr-14	445,720	493,556	9.69%
May-14	478,400	672,278	28.84%
Annual	7,448,116	8,406,745	11.40%

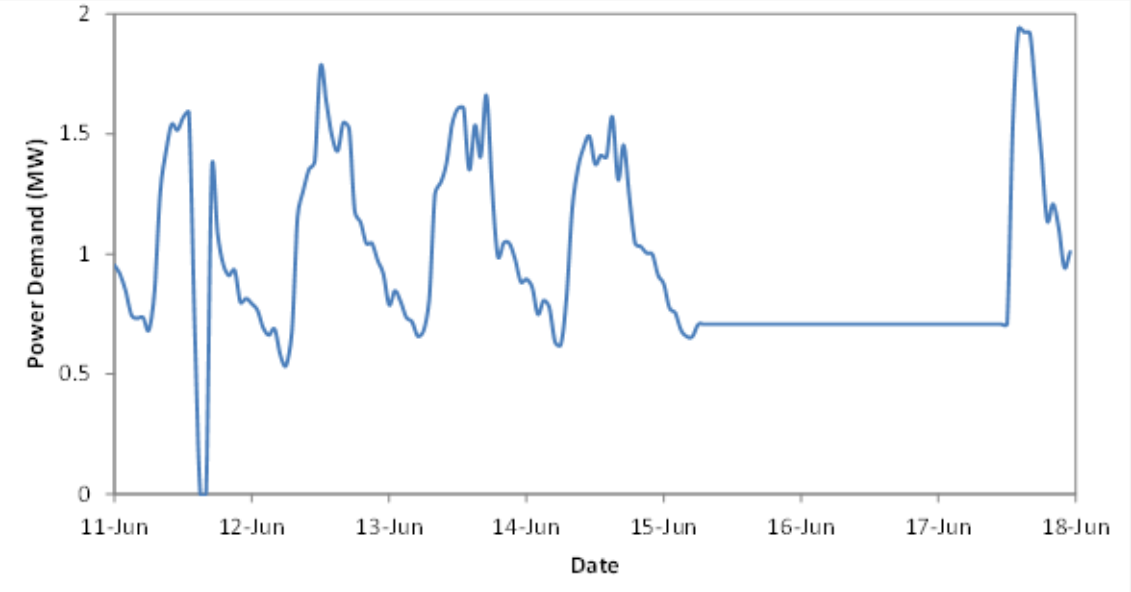


Figure 3.1 Power Demand of METU NCC without cleaning the data from June 11th, 2013 to June 17th, 2013

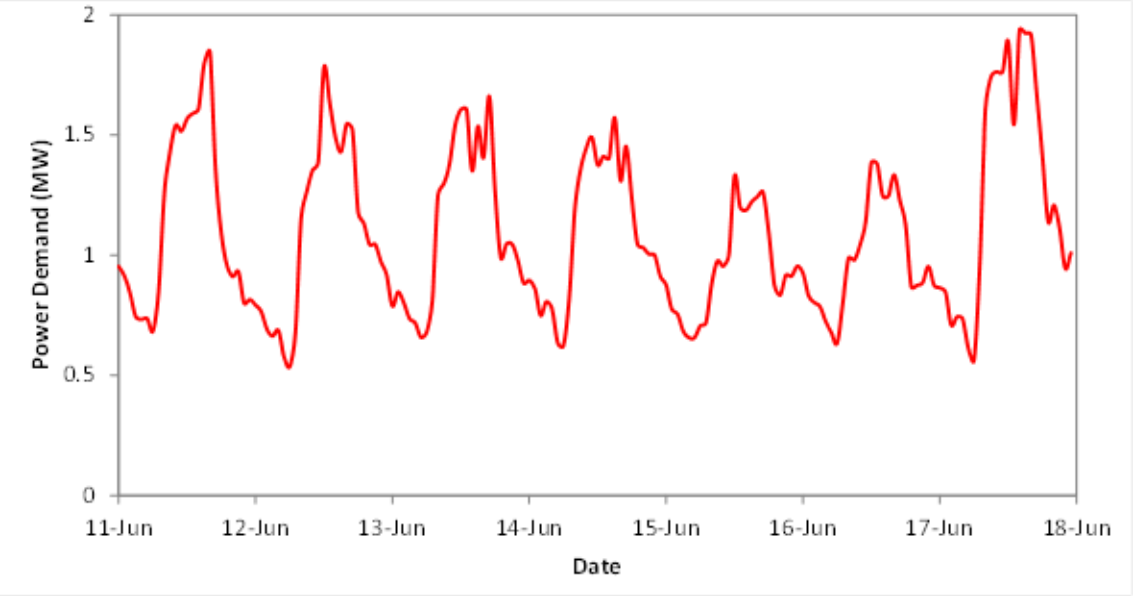


Figure 3.2 Power Demand of METU NCC with cleaned data from June 11th, 2013 to June 17th, 2013

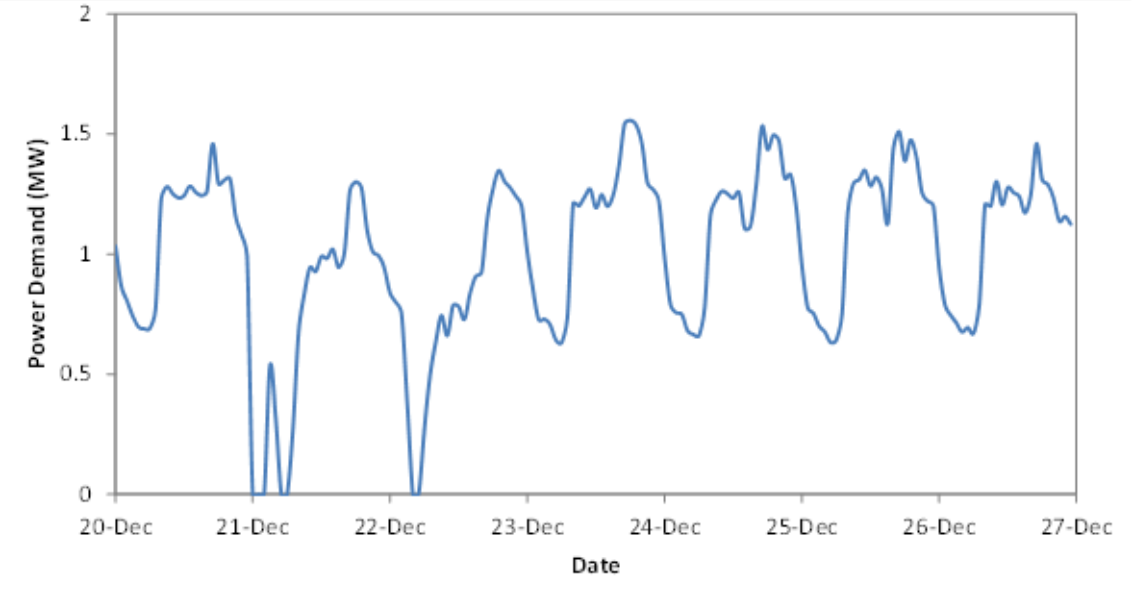


Figure 3.3 Power Demand of METU NCC without cleaning the data from December 20th, 2013 to December 26th, 2013

Figure 3.3 reveals the electricity demand of METU NCC from 20th December 2013 to 26th December 2013 without cleaning the data. It can be seen from the figure that the electricity demand falls to zero at the midnight of 21st December 2013 and stays like that till early morning of the same date. Almost similar pattern in the electricity demand happened early morning of 22nd December 2013. Figure 3.4 shows the electricity demand with corrected data. The data in Figure 3.4 will reflect the system performance more accurately compared to the data in Figure 3.3. It should also be noted in Figure 3.4 that the electricity demand on 22nd and 23rd December 2013 is comparatively lower than the other days because both of these days are also weekends.

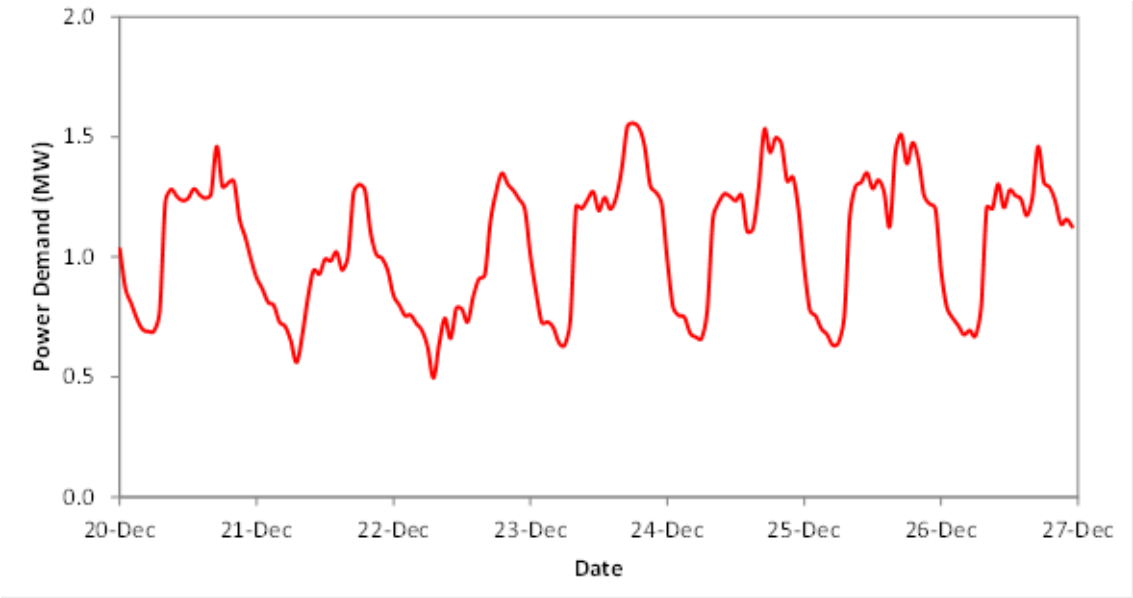


Figure 3.4 Power Demand of METU NCC with cleaned data from December 20th, 2013 to December 26th, 2013

3.1.4. Solar Data Acquisition

The PV energetic performance model requires inputs of the hourly solar resources and ambient temperatures. For METU NCC, the hourly solar resource model is based on actual solar resource measurements, which have been measured at METU NCC for more than a year. The solar resource data at METU NCC is being archived with respect to the standard time at the location. The solar resource model for the complete year was thus obtained as the measured data at the campus.

3.1.5. Solar Data Handling

The solar resource data being collected on-campus includes the measurement of the global horizontal irradiance and the direct normal irradiance. The solar resource data, average irradiation, is being archived for every 10 minutes in the campus. To convert it into hourly data, the data was first averaged over an hour and the process was repeated for the entire year.

3.1.6. Comparison of Solar Resource Data

The solar resource data from the PV power plant at Serhatköy, North Cyprus was extracted and the solar resource data at METU NCC was compared against it to check the correctness and data reliability of METU NCC data. The data was normalized by taking 1000 Wh m^{-2} solar insolation as the reference for both the data. Figure 3.5 presents the data comparison between the solar resources at METU NCC and Serhatköy PV power plant for a characteristic week in the Summer, from 1st July 2013 to 7th July 2013.

It can be observed from Figure 3.5 that the solar resource data at METU NCC has one hour lag from the Serhatköy solar resource data. The reason to that is, in Serhatköy, the data logger does not incorporate daylight savings time, which started on 30th March 2013. Other than that, both the data seem to be in agreement with each other. Figure 3.6 is presented after correcting the indicated problem in the data.

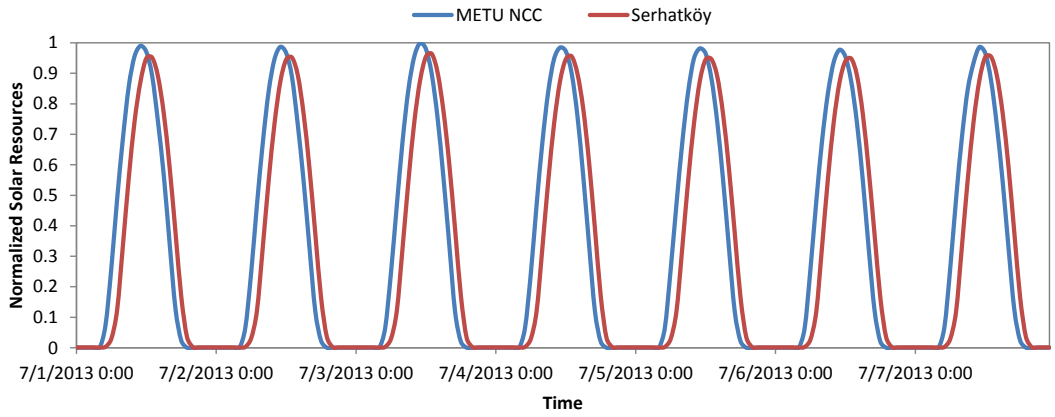


Figure 3.5 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Summer, from 1st July 2013 to 7th July 2013

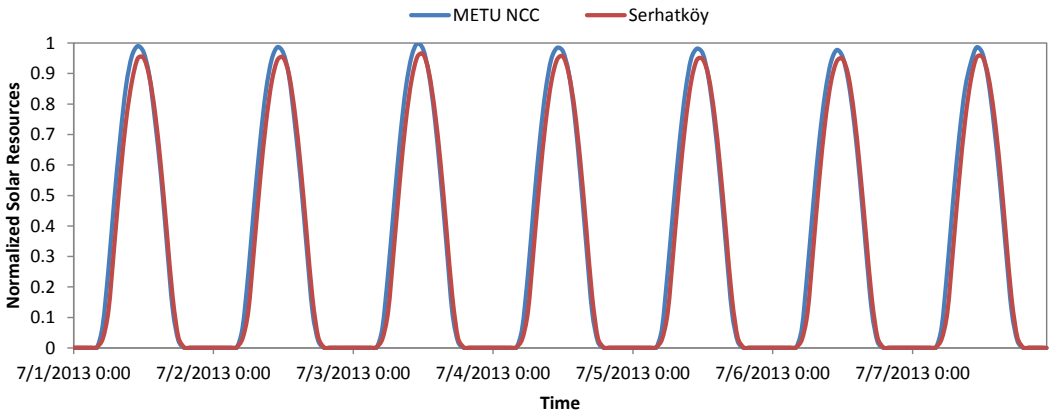


Figure 3.6 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Summer, from 1st July 2013 to 7th July 2013 with the daylight savings time problem fixed

Figure 3.7, like Figure 3.5, also presents the comparison between the normalized Solar Resources at METU NCC and Serhatköy. The period under consideration is between 8th August 2013 to 14th August 2013. It can be observed in Figure 3.7 that there is still a one hour difference between METU NCC and Serhatköy data and the solar resource data at METU NCC is lagging by one hour. Other than the lag, the data seems to be in good agreement for both the locations. Figure 3.8 is presented by correcting the DST problem in the Figure 3.7.

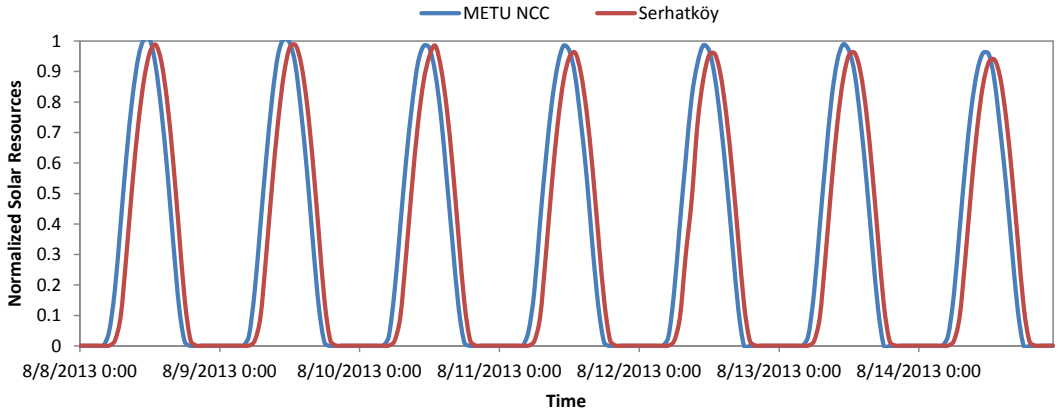


Figure 3.7 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Summer, from 8th August 2013 to 14th August 2013

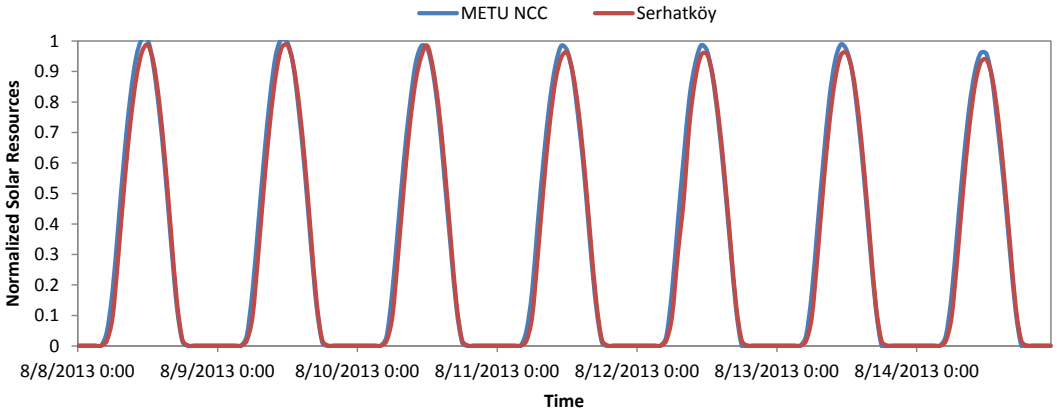


Figure 3.8 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Summer, from 8th August 2013 to 14th August 2013 with the daylight savings time problem fixed

To further check the correctness of the data, the period during the start of Fall season was also checked for both the locations and the resultant plot form the comparison is presented in Figure 3.9. It can be noticed that there still exists a one hour time difference between the two data and some inconsistencies in METU NCC data on 27th, 28th and 29th September 2013 as compared to the resources at Serhatköy. Other than the inconsistencies mentioned, the data seems to match fairly for both the locations. Figure 3.10 is the corrected version of Figure 3.9.

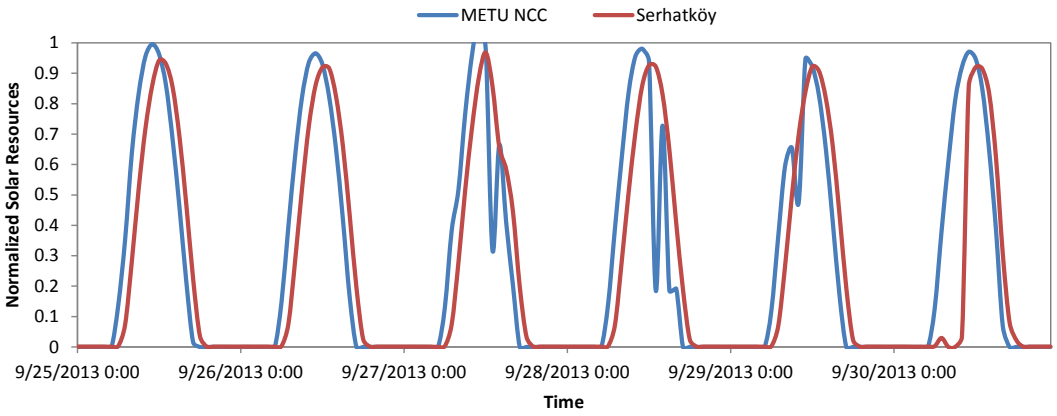


Figure 3.9 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Fall, from 25th September 2013 to 30th September 2013

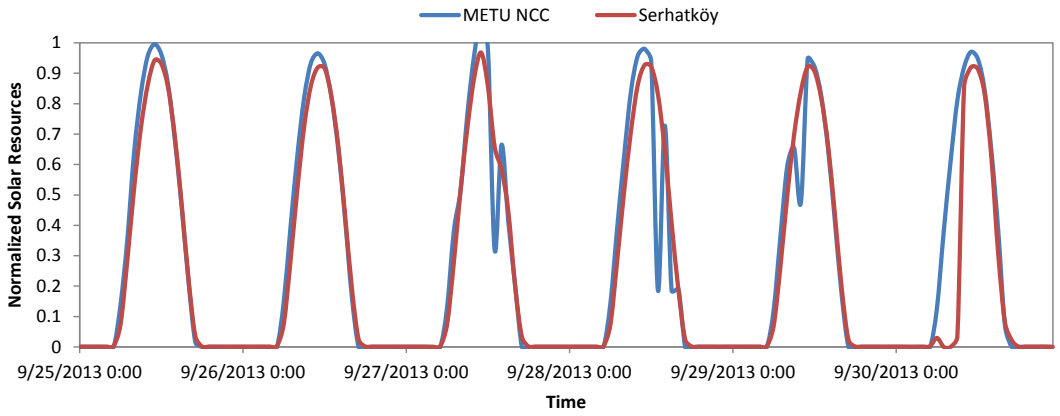


Figure 3.10 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Fall, from 25th September 2013 to 30th September 2013 with the daylight savings time problem fixed

A comparison between the two data was also made for a characteristic week in Winter. The period in Winter was taken as 17th January 2014 to 23rd January 2014. Figure 3.11 shows the results from the comparison between METU NCC and Serhatköy solar resource data.

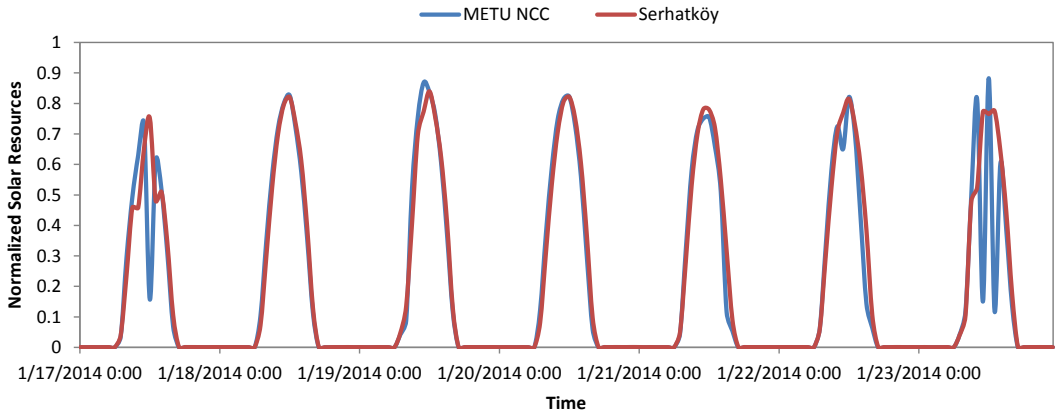


Figure 3.11 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Winter, from 17th January 2014 to 23rd January 2014

It can be observed that on clear days, the solar resources measured at METU NCC have a good agreement with the solar resources at Serhatköy. However, on cloudy days, the data do not

match well. Another important thing to be noted is that there is no time difference between the two data which is as expected since the daylight savings time ended on 26th October 2013.

Another characteristic plot for the comparison between the two solar resource data in Spring is presented in for the month of April 2014 in Figure 3.12. The data encompasses 12th April 2014 to 18th April 2014 solar resource data for METU NCC and Serhatköy. A one hour lag is again observed in the data which is as expected since the daylight savings started on 31st March 2014. A corrected version of Figure 3.12 is presented in Figure 3.13 and it can be observed that, on clear days, the data at METU NCC seems to have a good match with the Serhatköy solar resource data but on cloudy days, it seems to be much lower than the Serhatköy data. It can be seen that starting from 16th April 2014, the METU NCC data shows a decreasing trend as compared to the solar resource data at Serhatköy.

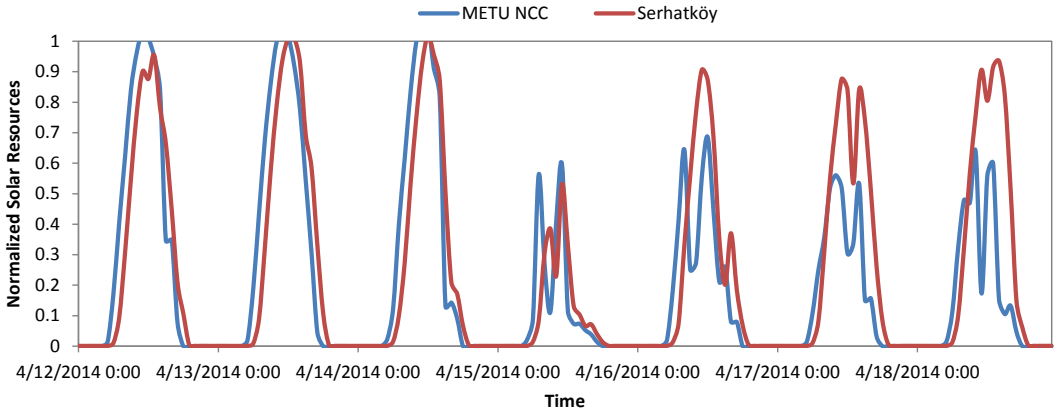


Figure 3.12 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Spring, from 12th April 2014 to 18th April 2014

Another characteristic plot for the month of May 2014 is presented in Figure 3.14. It can be seen clearly that the solar resources measured at METU NCC are significantly less compared to the solar resources measured at Serhatköy, North Cyprus, which indicates that there might be some problems associated with measuring the solar resource data at METU NCC.

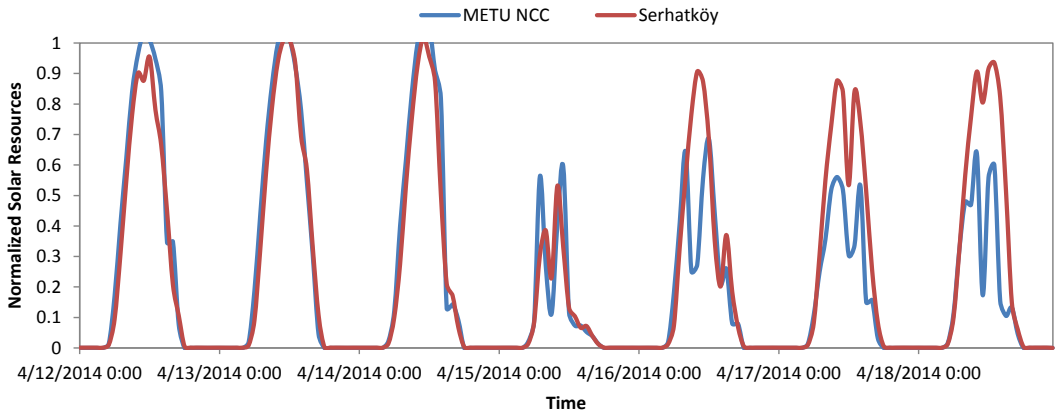


Figure 3.13 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in Spring, from 12th April 2014 to 18th April 2014 with the daylight savings time problem fixed

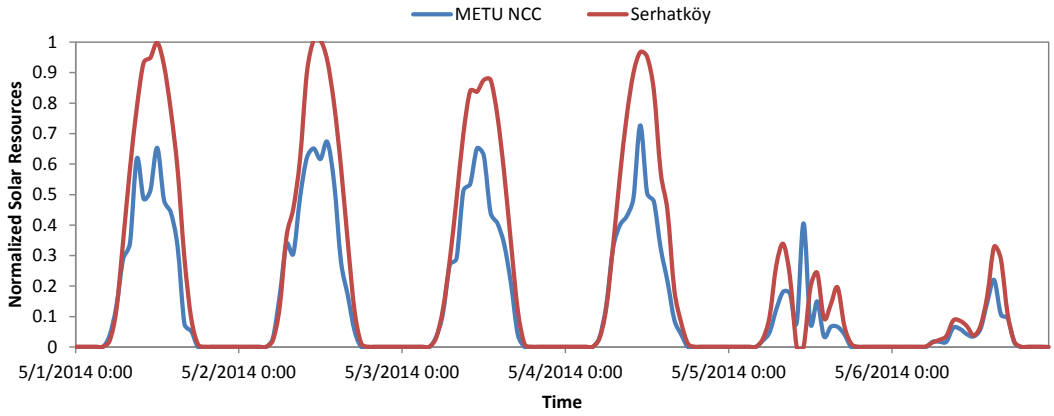


Figure 3.14 Comparison of Solar Resource Data measured at METU NCC and at Serhatköy, North Cyprus for a characteristic week in May, from 1st May 2014 to 6th May 2014

3.2. Mathematical Modeling

3.2.1. Solar Resource Model

The solar resource model is dependent upon a variety of factors. These equations are obtained from [46]. Explanation regarding the factors and representative mathematical equations are presented as follows:

Hour angle (*ω):* the angular hourly displacement of the sun by 15° per hour East or West in a day. Mathematically it can be expressed in Equation (4),

$$\omega = (solar\ time - 12) \times 15° \tag{4}$$

Equation (5) represents the conversion between standard and solar time.

$$Solar\ time - Standard\ time = \frac{1}{60}\{4(L_{st} - L_{loc}) + \mathrm{E}\} \tag{5}$$

Where,

L_{st} = Standard meridian of the local time zone

L_{loc} = Longitude of the location on which resources are to be measured

Solar time is the time based on apparent angular motion of the sun and the time at which the sun crosses the meridian of observer is called as solar noon. Standard time is the local time at the location with respect to the Greenwich Mean Time (GMT). Standard time cannot be used in solar calculations and has to be converted to solar time. A constant correction for difference in longitude between observer's meridian and the meridian on local time is required and the second correction is related to deviations in earth's rotation which result in affecting the time of sun crossing the meridian of observer.

'E' can be obtained by Equation (6) as follows,

$$E = 229.2(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \tag{6}$$

And 'B' can be found using Equation (7) as follows,

$$B = (n-1)\frac{360}{365} \tag{7}$$

Where,

n = day number (i.e. n = 1 for January 1 and 365 for December 31)

Declination (δ): the angle between the sun-earth line and equator and a vertical to the equator. Mathematically it is given by Equation (8) as,

$$\delta = 23.45 \sin\left(360 \frac{248 + n}{365}\right) \tag{8}$$

The declination angle is zero at the Spring and Fall Equinox (March 22 and September 22 respectively), reaches a maximum of 23.45° in the Summer Solstice (June 22) and attains the minimum value of -23.45° in the Winter Solstice (December 22).

Zenith Angle (θ_z): the angle between the vertical line and the sun-earth line. Mathematically it is represented as shown in Equation (9),

$$\cos\theta_Z = \cos\emptyset \cos\delta \cos\omega + \sin\emptyset \sin\delta \tag{9}$$

Solar Azimuth Angle (γ_s): the azimuth angle of the sun is defined as the angle from due south with angles west of south taking positive values and angles east of south taking negative values. Its mathematical form is presented in Equation (10). The sign function indicates the sign of γ_s whether it is positive or negative. It has a value of -1 when the value of ω is negative and it is +1 when the value of ω is positive

$$\gamma_s = \text{sign}(\omega) \left|\cos^{-1}\left(\frac{\cos\theta_Z \sin\emptyset - \sin\delta}{\sin\theta_Z \cos\emptyset}\right)\right| \tag{10}$$

Equation (11) provides the mathematical expression to calculate θ as

$$\cos\theta = \cos\theta_Z \cos\beta + \sin\theta_Z \sin\beta \cos(\gamma_s - \gamma) \tag{11}$$

The solar insolation that is obtained from the sun has three components, beam, diffuse and reflected insolation. Beam radiation is also referred to as direct insolation. It is used to define solar insolation that falls directly on the earth in a straight line. The diffuse insolation is the amount of insolation that reaches the surface after being reflected by the atmosphere. Reflected irradiation is the amount of insolation that has been reflected by buildings, structures, grounds

etc. As a first approximation the reflected insolation is neglected herein. The total insolation on a tilted surface is given as shown in Equation (12)

$$I_T = I_{bT} + I_{dT} \tag{12}$$

Where,

I_T = Total solar insolation on a tilted surface (Wh m^{-2})

I_{bT} = Beam insolation on a tilted surface (Wh m^{-2})

I_{dT} = Diffused solar insolation on a tilted surface (Wh m^{-2})

The beam insolation at a tilted surface can be calculated by using Equation (13)

$$I_{bT} = \text{DNI} \cos\theta \tag{13}$$

Where,

DNI = Direct Normal Insolation (Wh m^{-2})

The diffuse insolation on a tilted surface is represented by Equation (14)

$$I_{dT} = \left(\frac{1 + \cos\beta}{2}\right) I_d \tag{14}$$

Where,

I_d = Available diffused insolation on the surface (Wh m^{-2})

β = Surface Tilt (degrees)

Using the above equations, the solar resources at any location on earth for any hour of the day can be estimated if the DNI and diffuse horizontal solar resources are known.

3.2.2. Energetic model for PV

The efficiency and output energy of a PV system is known to be greatly influenced by the module temperature. The module temperature is dependent upon the module's thermal dissipation and absorption properties, irradiance, wind speed and installation surroundings [47]. The performance and efficiency of a PV system is decreased due to increase in the cell

temperature, primarily due to increased internal carrier recombination rates which are a result of increased concentrations of carriers in the PV cell [48].

The efficiency and power output of a PV system has an inverse relation with the cell temperature [49]. Usually a PV module transforms around 6 – 20% of the incident solar insolation into electricity while the rest contributes to increase the temperature of the panel by heat and in turn decreases the efficiency of the module [48]. So there is a certain need to account for the ambient conditions to accurately predict the performance and electrical output of the PV system while designing it. Some of the studies indicate the use of hybrid PV/Thermal systems to use the produced heat to generate electricity as well as use it to fulfill heating requirements [50].

Many correlations are present in the literature that depict the efficiency of the PV panels with respect to the changing ambient temperature. The most commonly used methods employ the use of Nominal Operating Cell Temperature, $NOCT$ in calculations. A simple mathematical relation often found in the literature [51] is said to produce satisfying results to calculate the cell temperature if the solar panels are not roof-integrated. The mathematical relation is given by Equation (15)

$$T_C = T_a + (\text{NOCT} - 20\ ℃)\frac{I_T}{800} \tag{15}$$

Where,

T_C = Cell temperature of PV Panel (°C)

T_a = Ambient temperature (°C)

$NOCT$ is provided by the manufacturer of the PV panel in the data sheet and technical specifications. A mathematical relation to obtain the efficiency of PV panels with varying cell temperature is repeatedly presented in the literature [49] [51] [52] which is shown in Equation (19)

$$\eta_c = \eta_{cr}\{1 - \lambda_c(T_c - T_{ref}) + \gamma \log I_T\} \tag{16}$$

Where,

η_c = Cell efficiency (%)

η_{cr} = Rated efficiency of PV panel (%)

λ_c = Constant, 0.0045 K^{-1}

T_{ref} = Reference temperature (°C)

γ = Material property, 0.12 for silicon

The value of η_{cr} is the rated efficiency of the PV panel, at Standard Test Conditions (STC). STC are taken as considering a solar irradiation of 1000 W m^{-2}, cell temperature of 25°C and air mass of 1.5. It is provided by the manufacturer and T_r is also taken as 25 °C. Most of the researchers have suggested to neglected the latter part of the equation [49] [51] [52]. However, it must be noted that the factor being neglected is actually greater than the first term and should not be neglected. Furthermore, if it is not neglected then the efficiency of PV panel seems to rise with the increase in cell temperature which yields erroneous output predictions. This suggests that the original equation which contains the neglected term, has either a typographical error or it is fundamentally wrong.

Considering the weakness in the model described earlier, a different model is used to estimate the efficiency of PV panel at every hour with respect to changing meteorological conditions. The model is also verified with measured data from the Solar PV Power Plant at Serhatköy, Northern Cyprus, and the details regarding the verification are presented in Chapter 4. The equation used to estimate the efficiency of PV panels with respect to varying meteorological conditions as given by [49] is as shown in Equation (17):

$$\eta_{PV} = \eta_{ref}\left[1 - \beta_{ref}\left\{T_a - T_{ref} + \left(NOCT - T_a\frac{I_T}{G_{NOCT}}\right)\right\}\right] \quad (17)$$

Where,

η_{PV} = Efficiency of PV panel (%)

$NOCT$ = Nominal Operating Cell Temperature (°C)

η_{ref} = Reference efficiency, calculated at STC (Standard Test Conditions) (%)

β_{ref} = Factor for efficiency calculations of PV (0.0045 $°C^{-1}$)

G_{NOCT} = Insolation at Nominal Operating Cell Temperature (800 Wh m^{-2})

3.2.3. Normalized model for coincidence

A normalized model for coincidence is defined in this sub-section. This model is used to do the sizing of PV panels with respect to the electricity demand. Coincidence refers to the point at which the electricity demand equals the electricity produced by the PV panels. Initially, the sizing of PV panels is done in a manner that excess electricity is not generated and there are minimum instances where the supply of electricity exceeds the electricity demand. It means that the system is sized in a way that at the nominal design time the electricity generated by the system is all consumed at the campus. Furthermore, normalization is used because normalized data has many benefits over actual data, including providing flexibility. Additionally, by normalizing, it is easier to define a size factor for PV modules, which defines the PV area relative to the nominal design area and can be used to optimize the area of PV collectors to meet the demand of the location under study.

The Normalized model for coincidence consists of the following steps:

The Normalized demand scales between 0 and 1 and is defined by Equation (18):

$$D'_E(\mathrm{t}) = \frac{D_E(t)}{D_{max}} \tag{18}$$

Where,

$D'_E(t)$ = Normalized demand at every hour

$D_E(t)$ = Electricity Demand at every hour (MWh)

D_{max} = Maximum Electricity Demand during the period used for analysis (MWh)

For example, the maximum hourly demand at METU NCC for the period of interest was approximately 2.72 MWh which occurred on 18th September, 2013 at 12:00 PM. A plot of trends in normalized demand (left axis) and electricity demand (right axis) are shown in Figure 3.15 for the period 15th September 2013 to 21st September 2013.

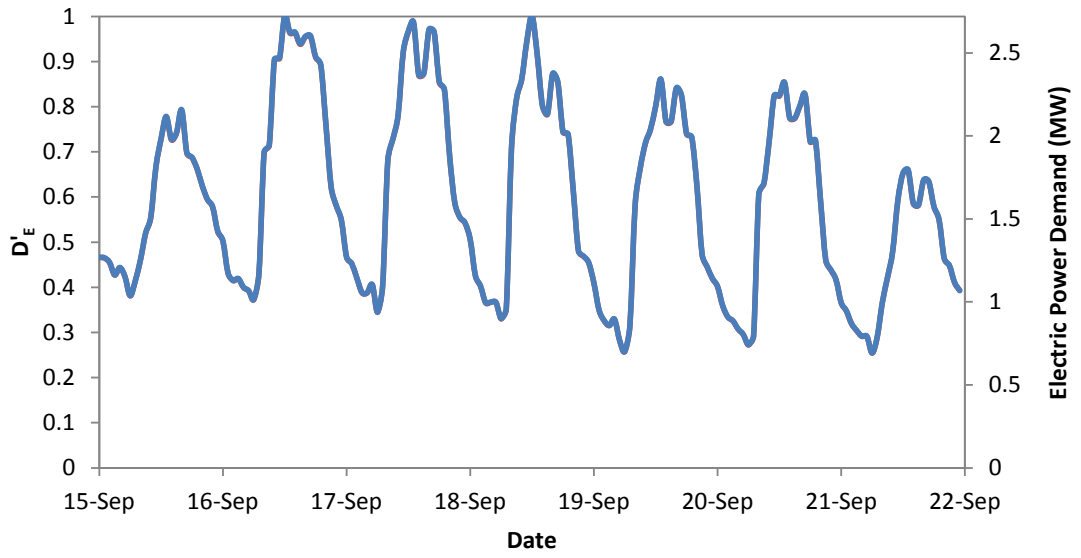


Figure 3.15 Trend in Electric Power Demand with Maximum Demand and Normalized Demand at METU NCC from 15th September, 2013 to 21st September, 2013

Figure 3.16 indicates the trend in Electric Power Demand and Normalized Demand for the time period where the minimum demand occurred not including blackouts. The minimum demand was on 31st August, 2013 at 6:00 AM which was around 0.31 MWh.

The normalized solar resource also scales between 0 and 1 and is obtained by using Equation (19) as follows:

$$I'_T(\mathrm{t}) = \frac{I_T(t)}{I_{max}} \tag{19}$$

Where,

$I'_T(t)$ = Normalized solar insolation at every hour

$I_T(t)$ = Solar insolation on a tilted surface at every hour (Wh m^{-2})

I_{max} = Maximum solar insolation for the selected period for analysis (Wh m^{-2})

For example, the maximum hourly solar resource at METU NCC for the period of interest was 1340 Wh m^{-2} which occurred on 8th of April, 2014 at 12:00 which was estimated to be on a tilted surface with the tilt equal to the latitude of North Cyprus (35° 12’ N). A plot containing the solar resources (right axis) and the normalized solar resources (left axis) is shown in Figure

3.17 for the period 5th April 2014 to 11th April 2014. It can be observed that 1340 Wh m^{-2} is a particularly high value for solar insolation and also the peak for the period under consideration is much higher compared to the other days. The reason to that may be that 8th April 2014 was partly cloudy, as observed from the jagged appearance on the plot and at 12:00, the solar resource monitoring station was not under a cloud and received high DNI. Also, a highly reflective cloud may have caused large I_d, thus increasing the overall solar resource.

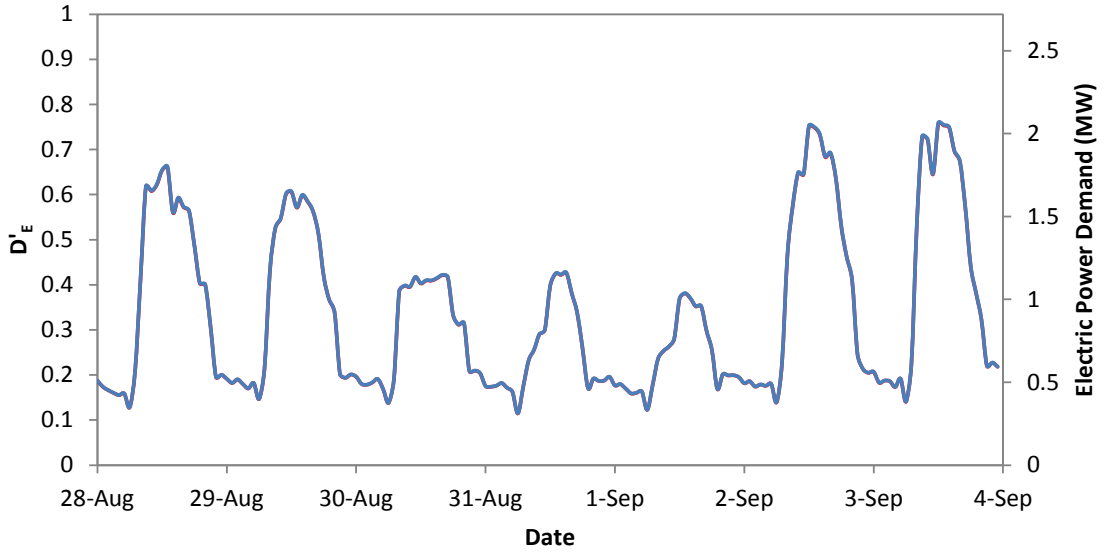


Figure 3.16 Trend in Electric Power Demand with Minimum Power and Normalized Demand at METU NCC from 28th August, 2013 to 3rd September, 2013

A similar plot is presented for the period between 7th December, 2013 to 13th December, 2013 in Figure 3.18. The plot shows variation in the solar resources for the period with the minimum daytime resources on the 11th of December 2013 with the lowest peak being 56 Wh m^{-2}.

After finding the normalized demand and normalized solar data, a coincidence coefficient, C_C is defined, which is calculated by the Equation (20) as follows:

$$C_C = \max\left(\frac{I'_T(t)}{D'_E(t)}\right) \tag{20}$$

While both D'_E and I'_T scale between 0 and 1, C_C can be larger than 1. As discussed above in Section 3.1.2, when calculating C_C the Demand Sizing Data Set was used to avoid instances where C_C goes to infinity due to D'_E going to zero.

This coincidence coefficient is used to determine the maximum utilization of solar resources to generate electricity while rarely exceeding the demand for any time of the time span considered as it would help determine the coincidence between demand and electricity generated at some point of time. The nominal design time, t_{ND} is obtained when

$$C_C(t_{ND}) = \frac{I'_T}{D'_E} \tag{21}$$

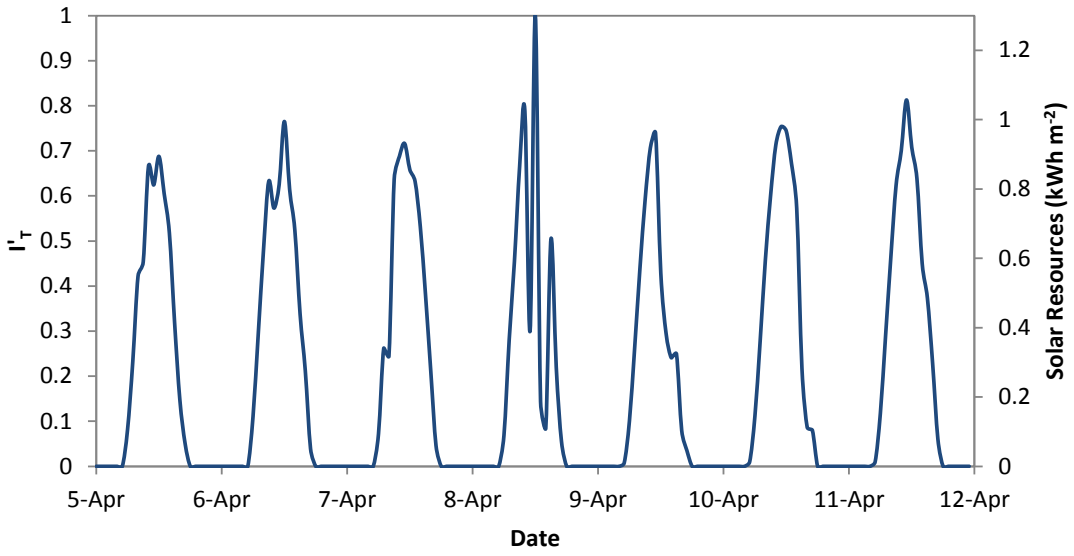


Figure 3.17 Actual Solar Resources with the Maximum Solar Resource and Normalized Solar Resources at METU NCC from 5th April 2014 to 11th April 2014

Scaled normalized solar resource coefficient is introduced, I'_{TC} which can be understood as the factor which determines the maximum utilization of solar resources without generating extra electricity. As discussed above, no net-metering or feed in tariff is employed in METU NCC at present, so this generation of excess electricity may not be important for locations that have net-metering or feed in tariffs. The scaled normalized solar resource coefficient can be obtained by the Equation (22)

$$I'_{TC} = \frac{I'_T(\mathrm{t})}{C_C} \tag{22}$$

For example the coincidence coefficient for the one year period under consideration at METU NCC was found to be 3.766, which occurred on 8th February 2014 at 11:00, which is therefore the nominal design time. A plot of normalized demand, normalized solar resources and nominal design time is presented in Figure 3.19.

Therefore $0 \leq I'_{TC}(t) \leq D'_E(t) \leq 1$ for all t.

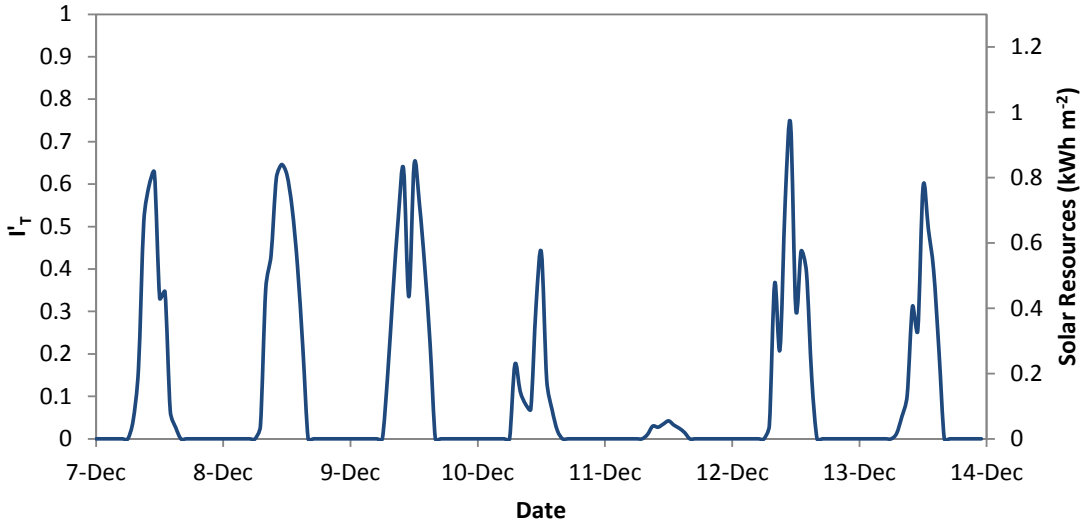


Figure 3.18 Actual Solar Resources and Normalized Solar Resources at METU NCC from 7th December, 2013 to 13th December, 2013

The nominal area of collectors A_N is obtained at the time of coincidence (nominal design time) as shown in Equation (23),

$$A_N = \frac{D_E(t_{ND})}{I_T(t_{ND}) \times \eta_{PV} \times \eta_{sys}} \tag{23}$$

Where at $t = t_{ND}$, $I'_{TC} = D'_E$ and at all times when $t \neq t_{ND}$ $I'_{TC} < D'_E$ and η_{sys} represents the performance ratio of the system, which scales between 0 and 1 and is usually of the order of 0.8

and incorporates the effects of heat losses, cabling shading and dust and most importantly the conversion between DC-AC power in the system [53].

The actual PV area A_S is defined using Equation (24), where S_F is the sizing factor which has unity value when area is equal to the nominal design area.

$$A_S = S_F \times A_N \tag{24}$$

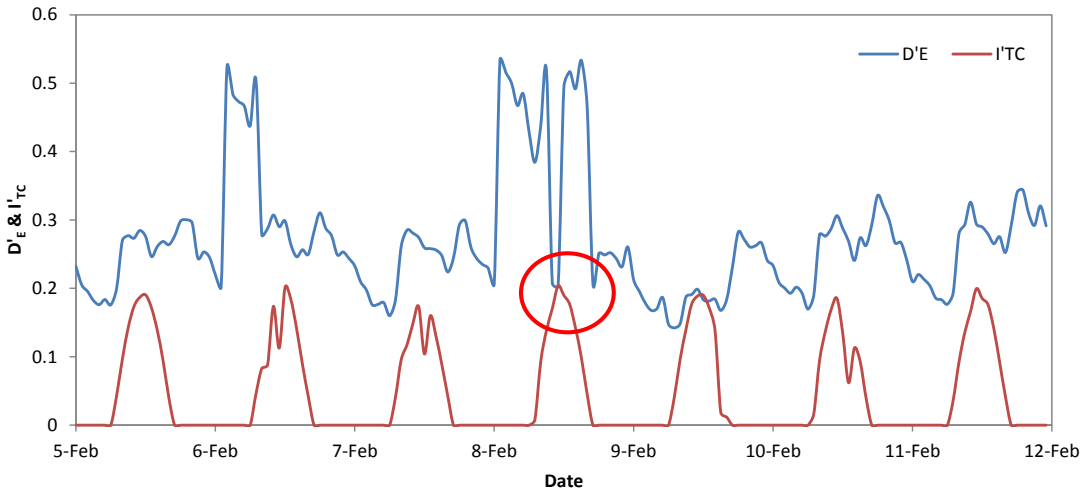


Figure 3.19 Normalized electricity demand and scaled normalized solar resources at METU NCC from 5th February, 2014 to 11th February 2014

Conceptually it is useful to treat the simplest case where installation costs are assumed to scale linearly with system size and the price of electricity is time invariant. For values of S_F less than or equal to 1, all of the electricity produced is consumed by the campus and the payback period of the system is constant as S_F varies. As S_F increases above 1, the system begins to produce more electricity than is required by the campus at specific points in time, this excess electricity is fed to the grid for free, and therefore the payback period begins to increase.

A term, solar fraction f_s is introduced which is the ratio of the electricity being produced by the PV panels and being consumed by METU NCC to the total electricity demand of the campus for some time period, which is typically 1-year. Mathematically it is shown in Equation (25),

$$f_s = \frac{Electricity\ produced\ by\ PV\ and\ consumed\ by\ METU\ NCC}{Total\ Electricity\ Demand} \quad (25)$$

The solar fraction is used to estimate the level of PV penetration with different values of S_F and different orientations.

3.2.4. Economic Model

The economic analysis is performed by calculating NPV (Net Present Value) for the PV power plant to be installed. NPV is selected because it gives a very good idea about the feasibility of a project. First the cost of the PV system is obtained. At a minimum, PV system cost model contains the PV panel cost, inverter cost, BOS and storage cost (if storage is considered). The system may also contain the cost of inspection, permitting cost, installation cost and other auxiliary equipment etc. (which are referred to as soft costs), which can be around 60% of the total cost [20]. Electricity generated from PV panels can be stored in batteries to be used at night times when there is no electricity production from PV. This research does not incorporate the option to store electricity generated as batteries are expensive and also generate a lot of waste after their productive life is finished. The cost analysis of the PV system is calculated for three different cases:

1) Assuming no soft costs; i.e. minimum capital
2) Soft costs included in the capital cost as 60% of the total cost i.e. maximum capital costs
3) Average of the maximum and minimum capital costs

The cost of PV system can be obtained by Equation (26):

$$C_{PVS} = c_p \times C_{PV} \quad (26)$$

Where,

C_{PVS} = Total Cost of PV system (USD)

c_p = Capacity of Power Plant (kW)

C_{PV} = Cost of PV module (USD kW^{-1})

The cost of inverter system can be obtained by the Equation (27):

$$C_{IS} = c_I \times C_{IU} \quad (27)$$

Where,

C_{IS} = Cost of Inverter System (USD)

c_I = Capacity of Inverter (kW)

C_{IU} = Cost of Inverter module (USD kW^{-1})

Assuming no soft costs, the cost of power plant can be obtained as shown in Equation (28)

$$C_{PP} = C_{IS} + C_{PVS} \quad (28)$$

Where,

C_{PP} = Cost of Power Plant (USD)

If the soft costs are included, they are taken as 60% [54] of the total capital cost and the economic analysis is performed using the increased capital cost. The economic benefits can be quantified in terms of the amount of electricity not required to be purchased from the grid, i.e., the amount of electricity generated from the PV power plant and consumed by the campus. The economic benefits can thus be calculated as present in Equation (29),

$$C_{EB} = TE_{GE} \times C_{TGE} \quad (29)$$

Where,

C_{EB} = Economic Benefits (USD)

TE_{GE} = Total Energy Generated using Solar PV power plant and consumed on campus (kWh)

C_{TGE} = Total Cost of Grid Electricity (USD kWh^{-1})

The total cost of grid electricity is obtained by Equation (30) as,

$$C_{TGE} = C_{GE} + VAT \quad (30)$$

Where,

C_{GE} = Cost of Grid Electricity (USD kWh^{-1})

VAT = Value Added Tax (USD kWh^{-1})

The net economic benefits can thus be calculated as presented in Equation (31),

$$C_{NEB_y} = C_{EB} - I_C - M_C \tag{31}$$

Where,

C_{NEB_y} = Yearly Net Economic Benefits (USD)

I_C = Insurance Cost (USD)

M_C = Maintenance Cost (USD)

Insurance Cost is assumed to be 0.25% of the total capital cost of the power plant [55] and is assumed constant for every year. Maintenance Cost of the system is assumed to be 1.5% of the initial cost of the PV power plant [56]. This value of Maintenance Cost is also close to the value reported by [55].

The NPV is then obtained as shown in Equation (32) as follows

$$NPV = \sum_{0}^{y} C_{NEB_y} \times f - C_{PP} \tag{32}$$

Where, the factor, f is given by Equation (33) as,

$$f = \frac{1}{(1+i)^y} \tag{33}$$

Where,

i = interest rate (%)

y = Number of year (i.e. 1, 2, 3, ….)

Another performance metric regarding economic analysis is Levelized Cost of Energy, $LCOE$. It is often used for marketing by PV equipment producers and is also related to analyses regarding

utility-scale projects. $LCOE$ is used to relate the comparative cost of energy produced by various energy-generating sources, irrespective of the project's scale or functioning time frame [57]. It is the cost of energy produced per unit output energy during the lifetime of the PV system and is mathematically given by Equation (34) as,

$$LCOE = \frac{C_{PP} + \sum_{t=1}^{y}(I_C + M_C) \times f}{\sum_{t=1}^{y} E_{TP} \times f} \quad (34)$$

Where,

$LCOE$ = Levelized Cost of Energy (USD kWh^{-1})

E_{TP} = Total Energy Produced during lifetime of the PV power plant (kWh)

3.2.5. Ecological Model

The Ecological Model herein only quantifies the impact of the system on climate change, and not in terms of other pollutants. If the rate of emissions associated by combustion of fuel in a power plant are defined by the variable E_r, then the amount of CO_2 emitted per MWh due to the electricity consumption of the location can be obtained by Equation (35)

$$A_{CO_2}(\mathrm{t}) = D_E(\mathrm{t}) \times E_r \quad (35)$$

Where,

$A_{CO_2}(t)$ = Amount of CO_2 emitted per hour (kg)

E_r = Emission rate of combusting fuel (kg MWh^{-1})

The amount of CO_2 avoided can be quantified in terms of the reduction in the electricity demand of the campus due to the installation of the PV power plant. If $R_D(t)$ is the reduced electrical demand, then it can be mathematically expressed by Equation (36)

$$R_D(\mathrm{t}) = D_E(\mathrm{t}) - E_{GE}(\mathrm{t}) \quad (36)$$

Where,

$E_{GE}(t)$ = Energy generated by the solar PV Power Plant and consumed on the location at every hour (MWh)

The amount of CO_2 reduced due to electricity generated by PV can be calculated by Equation (37)

$$A_{RCO_2}(\mathrm{t}) = R_D(\mathrm{t}) \times E_r \tag{37}$$

Where,

$A_{RCO_2}(t)$ = Reduced amount of CO_2 emitted per hour (kg)

Finally, the total CO_2 emissions avoided can be calculated as shown in Equation (38)

$$TA_{RCO_2} = \sum A_{CO_2}(\mathrm{t}) - \sum A_{RCO_2}(\mathrm{t}) \tag{38}$$

Where,

TA_{RCO_2} = Total Reduced amount of CO_2 emitted per hour (kg)

CHAPTER 4

APPLICATION OF METHODOLOGY TO METU NCC

This chapter is an application of the methodology delineated in Chapter 3. First the sizing of the PV panel is performed using the coincidence model explained earlier. After determining the size of the system, the energetic model is used to estimate the efficiency of the system and the performance of the system is explained. The chapter then proceeds by portraying different parametric studies regarding the sizing of the system. After that, the chapter presents an economic analysis followed by ecological assessment of the proposed project at METU NCC at the end of the chapter.

4.1. Verification of PV Energetic Model

As discussed in Section 1.2, North Cyprus has a 1.3 MW solar PV power plant at Serhatköy, Güzelyürt. Data were extracted from the website for verification [58]. The data for each day were downloaded and processed, which took approximately 10 minutes for each day or approximately 60 hours. The data obtained from the website were Mean Irradiance (W m^{-2}) on the PV panels (25° and 180° azimuth), ambient temperature (°C) and average hourly power output of the system (kW).

The Energetic PV Model as explained in Section 3.2.2 was verified by using these measured data at Serhatköy, North Cyprus. Several characteristic days were selected for the verification of the model based on the consistency of available solar resource data on that particular day. The days selected were 1st June 2013, 15th December 2013, 22nd December 2013, 4th March 2014 and 20th April 2014. These days include days with both high and low solar insolation and for all the seasons for the entire year selected to be presented as a case study in this research. Figure 4.1 up to Figure 4.5 show the difference in the measured and calculated power for the entire days selected. It can be observed from the results that the Energetic model has good agreement with the actual measured data at Serhatköy, North Cyprus. For a hot day with good solar resource, the model over-predicts the power slightly. For a cold day, however, the model under-predicts the power output. The reason to this may be explained in terms of meteorological

conditions that since in winter, the ambient conditions were cold and this model does not account for any wind factor, it may be said that it is under-predicting due to this fact. Furthermore, for slightly high power output predicted, it may be stated that since this model does not account for any dust factor, it predicted slightly high power output. While these reasons are purely speculation, since the predictions are sufficiently close to the actual output for the purposes of this work, the source of these differences was not investigated further.

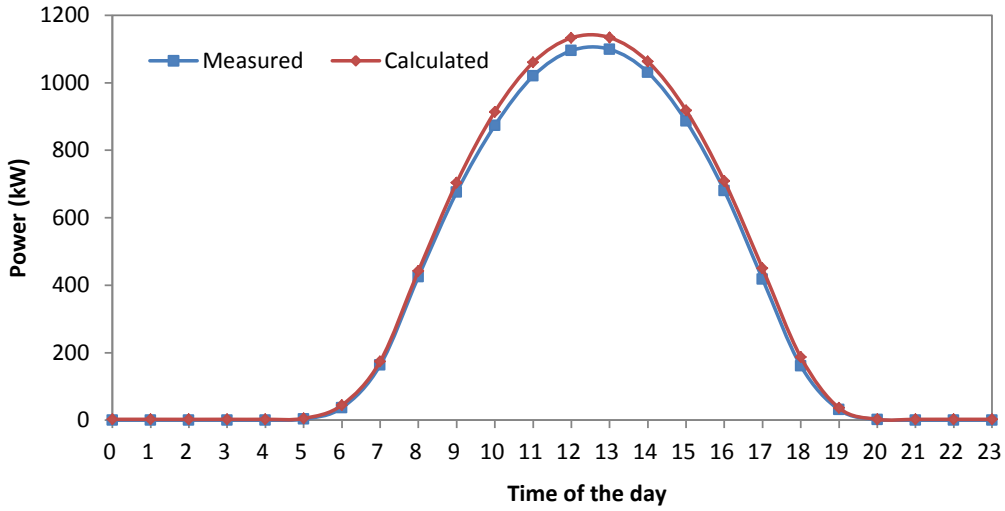


Figure 4.1 Comparison between calculated power and measured power at Serhatköy, North Cyprus for 1st June 2013

The efficiency of the power plant at Serhatköy, North Cyprus was calculated using the measured power and was compared against the efficiency calculated by the Energetic Model. Figure 4.6 and Figure 4.7 show the efficiencies plot for 1st June 2013 and 15th December 2013 respectively.

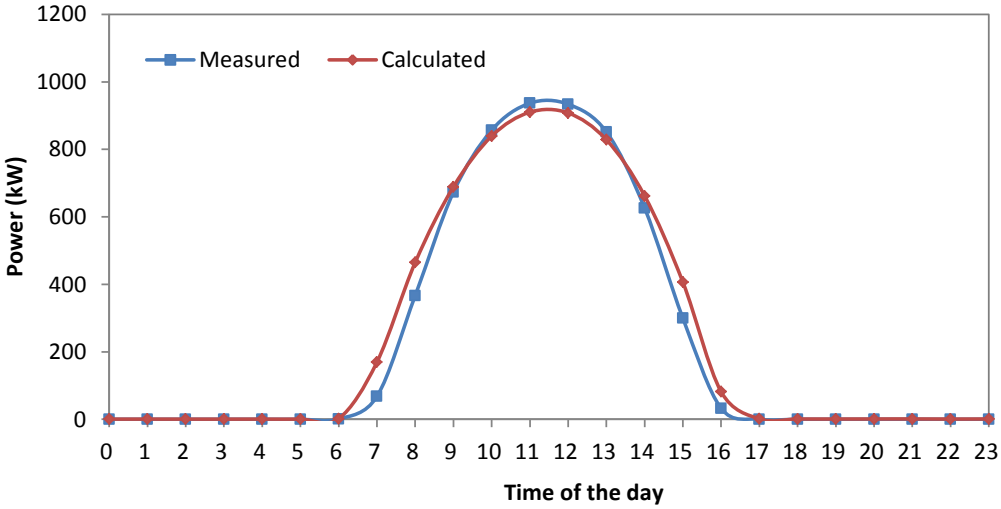


Figure 4.2 Comparison between calculated power and measured power at Serhatköy, North Cyprus for 15th December 2013

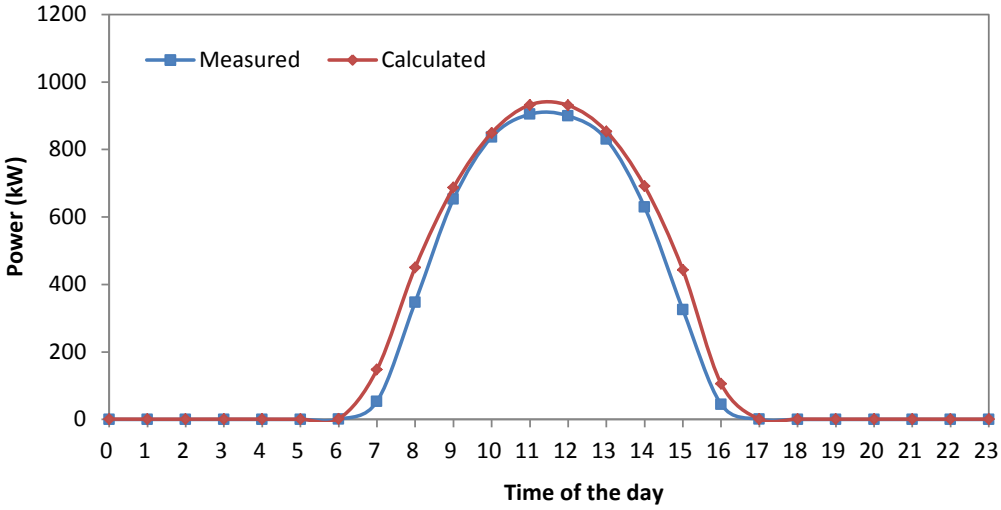


Figure 4.3 Comparison between calculated power and measured power at Serhatköy, North Cyprus for 22nd December 2013

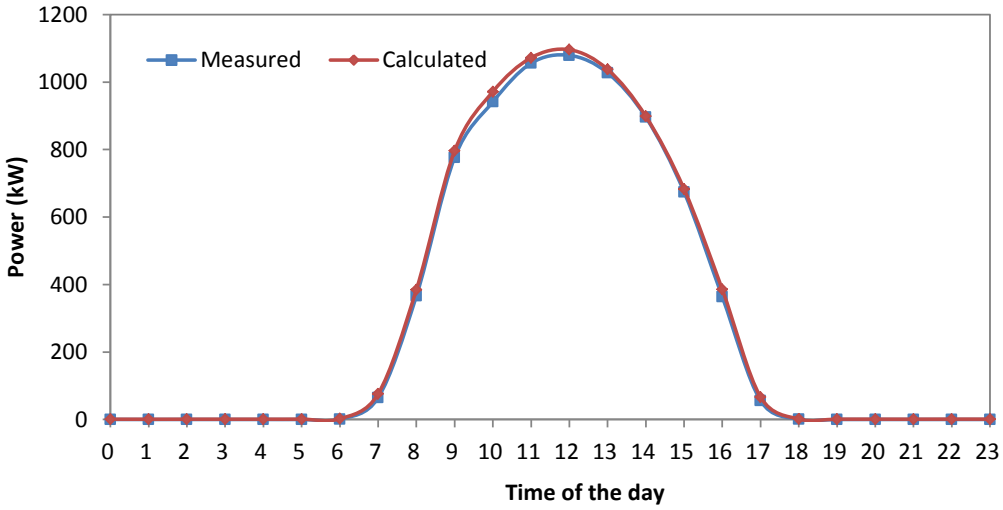


Figure 4.4 Comparison between calculated power and measured power at Serhatköy, North Cyprus for 4th March 2014

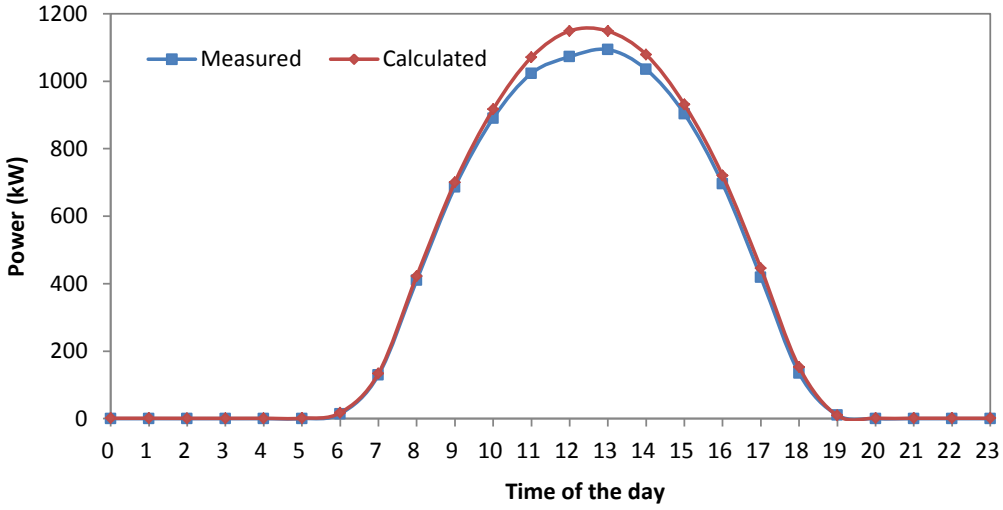


Figure 4.5 Comparison between calculated power and measured power at Serhatköy, North Cyprus for 20th April 2014

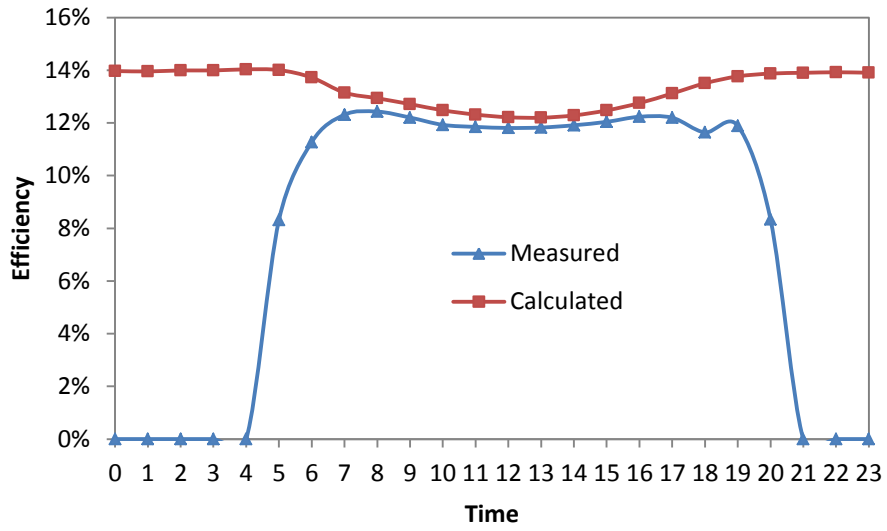


Figure 4.6 Calculated efficiency and measured efficiency at Serhatköy, North Cyprus, for 1st June 2013

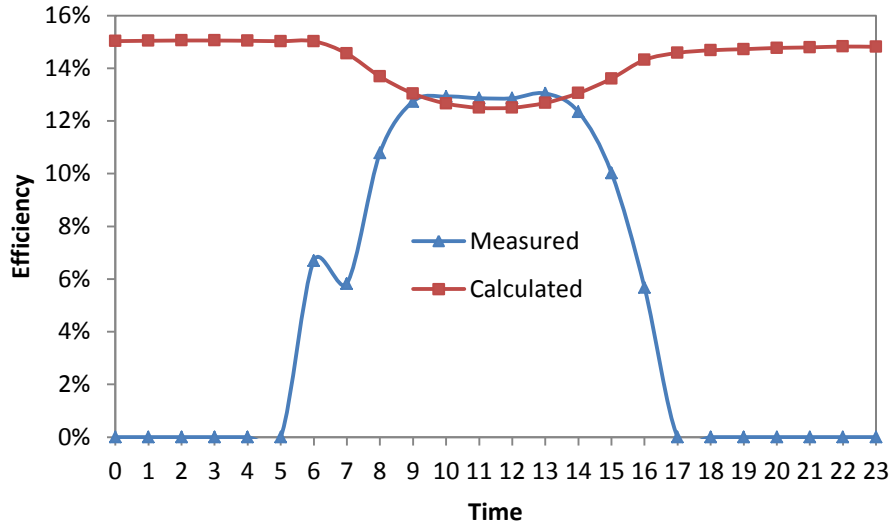


Figure 4.7 Calculated efficiency and measured efficiency at Serhatköy, North Cyprus, for 15th December 2013

These two days were selected out of the 5 days presented before to present an idea about the variation in efficiencies for both a very hot and a very cold day. The results indicate that the measured efficiency does not drop to zero during the beginning and end of the day.

Furthermore, since no electricity is being generated at night times from the PV panels, it can be stated that predicting the efficiency at night time is not useful. The reason for the efficiency not being accurately predicted at night times and very early mornings can be explained in the manner that this happens because the Energetic Model presented has dependency upon the reference efficiency, η_{ref}, which is measured for the PV module at $NOCT$. Whereas while estimating the measured efficiency from the measured data, it is zero in the early and late hours of the day since the power output of the system is zero. In the hours with high incident solar insolation though, it can be observed from the Figure 4.6 and Figure 4.7 that there is not much difference in the measured and calculated efficiencies. In conclusion, during the mid-day hours where most of the PV output occurs the measured and predicted efficiencies are similar. During sunrise and sunset times significant deviations exist between the measured and predicted efficiencies, possibly due to high reflectance associated with large angle of incidences that is not included in the Energetic Model, but since the PV output during these hours is small these deviations are not critical for the purposes of this work. In conclusion, the Energetic Model is considered sufficiently accurate for this research.

4.2. Sizing of PV panels and system

4.2.1. Nominal Design Area

The Nominal Design Area was obtained by using the Coincidence Model as explained in Section 3.2.3. The Nominal Design Time was obtained by using three different meteorological data sources: 1. METU NCC measured solar resource data; 2. synthetic TMY2 (Typical Meteorological Year) data; and 3. the Solar Resource Data obtained from the Serhatköy Power Plant [58]. Table 4.1 reflects the comparison of the sizing performed by using the three different data sources.

The TMY2 data and data measured at METU NCC were used with the Solar Resource Model as explained in section 3.2.1 and resources on a tilted surface with the tilt angle equal to the latitude of the location were used. The Serhatköy data, however was used considering it at a tilt angle of 25°. It can be observed from Table 4.1 that the Nominal Design Area according to data obtained from METU NCC station is 4871 m^2. To elaborate this further, it can be stated that for a PV area of 4871 m^2, the system will produce as much electricity as the campus will consume at that the Nominal Design Time and when the area is increased further than this particular value, the system will overproduce electricity at least at the Nominal Design Time.

Table 4.1 Comparison of PV system Nominal Design Time and Area using different data sources

Solar Resource Data Source	**Nominal Design Time**	**Nominal Design Area**
-	**-**	**m^2**
METU NCC	8th Feb 2014, 11:00	4871
Serhatköy	20th Apr 2014, 12:00	5041
TMY2	23rd Feb 2014, 11:00	4910

It can also be observed that there are not large differences in the Nominal Design Areas for the different data sources, which suggests that a Nominal Design Area of approximately 5000 m^2 is probably robust. Whether this result of actual or synthetic TMY2 data yielding similar Nominal Design Areas as actual solar resources can be generalized to other locations or is unique to this case study should be explored. If synthetic or actual TMY2 data can be substituted for actual meteorological data for all locations, then there may not be any need to invest in a measurement station and synthetic TMY2 data would be sufficient to design a PV system for a specific location using this methodology. The plots containing the nominal design time by using Serhatköy data and TMY2 data are presented in Figure 4.8 and Figure 4.9 respectively. Recall the nominal design time using METU NCC data is presented in Figure 3.19.

The total electricity requirement for METU NCC during the entire selected year is found to be approximately 8.5 GWh. To generate this much electricity annually, a PV area of approximately 40,000 m^2 is required, or about 8 times the nominal design area. However, it must be noted that not all the electricity produced by the system would be consumed by the campus and a large portion of the electricity would be provided to the utility company for free. Figure 4.10 shows the total electricity generated by the PV system with an area from 0 to 40,000 m^2 and the total electricity consumed by METU NCC.

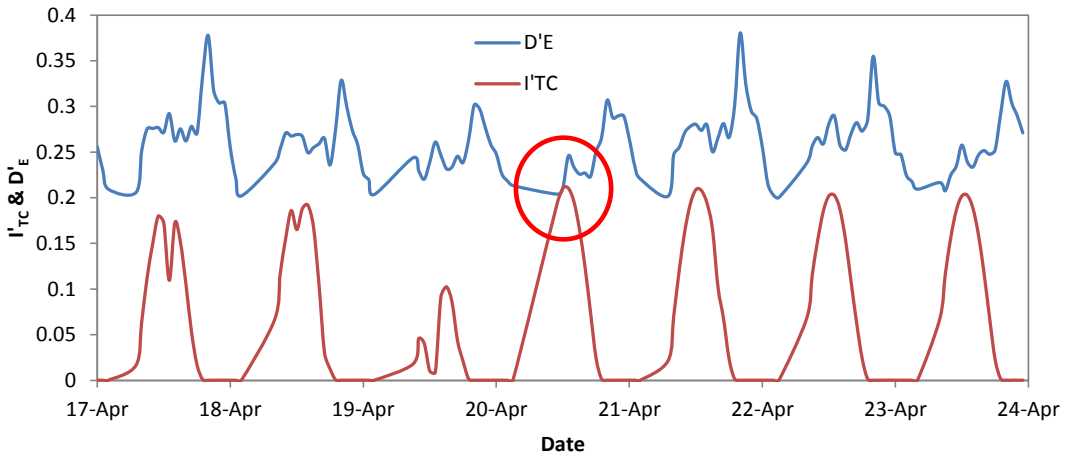


Figure 4.8 Nominal Design Time for the PV system using data measured at Serhatköy, North Cyprus

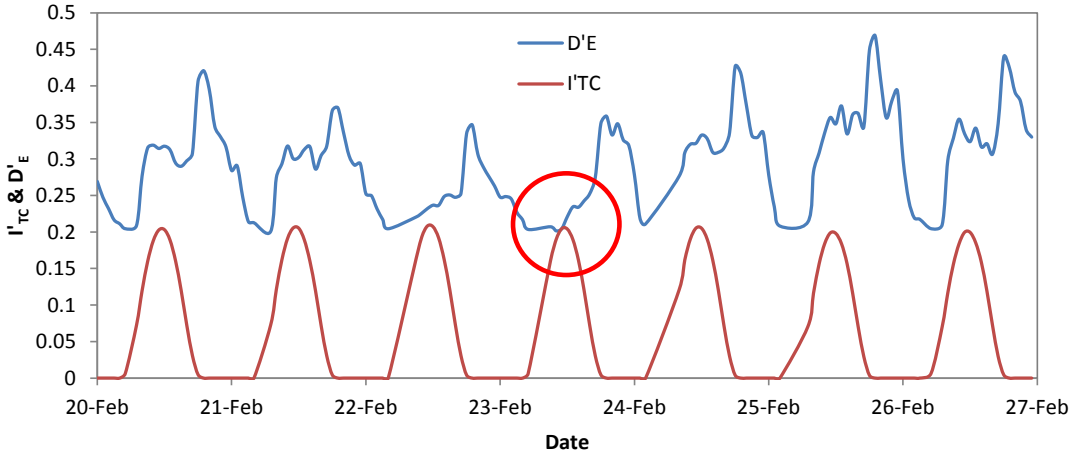


Figure 4.9 Nominal Design Time for the PV system using synthetic TMY2 data set for Güzelyurt, North Cyprus

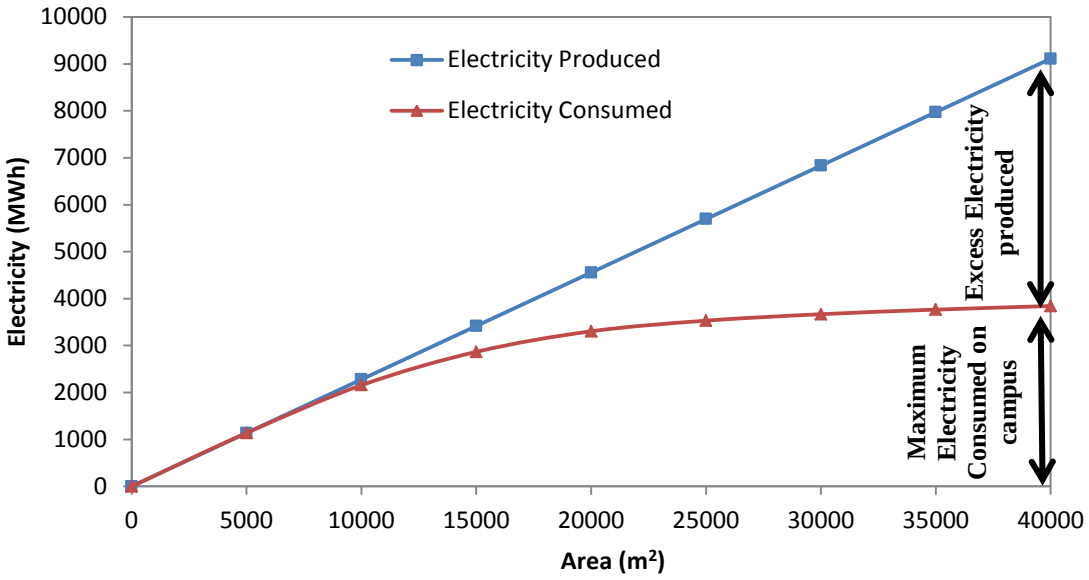


Figure 4.10 Trend between Total Electricity Produced by PV and PV electricity Consumed with varying area of PV Panels. The total electricity demand for this 1 year period is 8.5 GWh

Figure 4.10 also indicates that as the area of PV panels is increased from 0 to ∞, the amount of electricity generated by the panels increases linearly but the total electricity produced by the PV and consumed by the campus first increases linearly up to the nominally design area but then asymptotically approaches some value. This happens because as the area of the panels is increased beyond the nominal design area, excess electricity begins to be produced and is fed to the grid for free. Since the PV system being designed does not incorporate any storage, it means that no electricity is being generated at night times and the university has to pay to the utility for all electricity consumed at night regardless of the size of the PV system. In addition to that, during the day, due to generation of excess electricity during some times when electricity demand is less than the electricity being produced, the university is bearing another loss while the utility company is being benefitted because the university is providing electricity to the grid for free. So even if a PV area is installed to generate all the electricity required by the campus for a year, a zero electricity bill for the university will be impossible since there is no storage considered and one-way metering is used.

4.2.2. Maximum PV Penetration at METU NCC without generating excess electricity

Another parametric study was performed to investigate the maximum limit to which electricity generated through the PV power plant at METU NCC would substitute for the grid electricity, considering no overproduction of electricity from the PV power plant. It was observed that the maximum PV penetration quantified as the solar fraction at METU NCC is 13% if no electricity in excess is generated. Figure 4.11 shows the different levels of PV penetration with varying Size Factors.

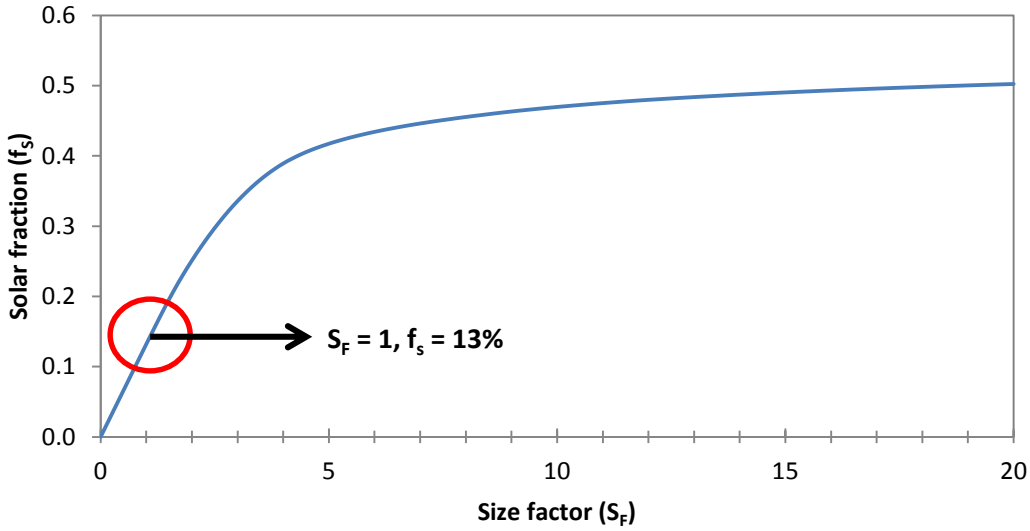


Figure 4.11 Different levels of PV penetration in the electricity demand profile of METU NCC with varying Size Factors

It can be observed from Figure 4.11 that as the Size Factor is increased from 0 to 1, the level of PV penetration to meet the electricity demand of the campus increases linearly. At a Size Factor of 1, i.e. the nominal design area, the maximum fraction of electricity produced for METU NCC is 13%. As the Size Factor is increased from 1 to ∞, the maximum penetration level of PV increases. However, it can be observed that after the Size Factor of 1, the trend of the solar fraction increase shifts from linear to asymptotic. The maximum level of PV penetration for a Size Factor of 20, which corresponds to a PV area of approximately 97500 m^2 is around 50% and is depicting an almost constant value even if the Size Factor is increased further. An important point to be considered while considering the results from Figure 3.10, however, is

that no matter if the Size Factor is increased beyond 1, it will contribute to more PV penetration but it will lead to generation of excess electricity, which will increase the payback period of the power plant and lead to economic losses to the university. In conclusion, in the limit as the PV area approaches infinity, approximately 50% of the required electricity of the campus can be generated using PV, which conceptually makes sense since no matter how large the PV system it can never produce electricity at night, which is 50% of the year.

4.2.3. Sizing of inverter

The inverter size is an important factor while sizing a PV system. All the PV modules are tested and have a rated performance at Standard Test Conditions (STC). The conditions at STC do not occur for most of the time during the year because very seldom do all the conditions required for STC happen simultaneously. To account for the fact that typically the PV panels are not operating at STC and additionally, the wear and tear of the PV panels, losses due to increase in cell temperature and other losses, the PV system is oversized compared to the inverter size by a factor in the range of 1.1 to 1.3 [54].

A study was performed by varying the size of inverter with varying Size Factors and the effects were observed on the $LCOE$ of the system. $LCOE$ is calculated for all the Size Factors assuming a PV to inverter size ratio of 1.2, an interest rate of 15%, same as the NPV. The maintenance and insurance costs, as explained in section 3.2.4, were taken as 1.25% and 0.25% of the total capital cost and are assumed to be constant throughout the life time of the power plant. Figure 4.12 shows the plot containing the study to define a feasible PV to inverter ratio. The results indicate that $LCOE$ does not vary significantly with varying PV to inverter size ratio. The $LCOE$ of the system is constant from 0.2 up to the Size Factor of 1. However, increasing the Size Factor beyond the nominal value of 1, increases the $LCOE$. Additionally, the PV to inverter size ratio of 1.3 seems to achieve the lowest $LCOE$, which is not significantly different from a size ratio of 1. Although not evident from the figure, while performing the parametric study, it was observed that a Size Factor of around 6.2 makes the $LCOE$ equivalent to the current grid electricity cost of 0.24 USD kWh^{-1}.

The PV panel considered for this case study was SYP240S of Risen Energy Ltd [59] . The inverter selected was SOLEOS OXYGEN 14_21-TL3 of Soleos Solar GmbH [60]. The interest rate, i was selected 15% as given in [61] for most energy projects. The rated capacity of the PV

power plant was found to be 720 kW, considering the nominal design area. The capacity of PV to inverter ratio was selected as 1.2 [54], making the inverter capacity of 600 kW. The life-time of the PV power plant was assumed to be 20 years [34]. The insurance cost, I_C was assumed to be 0.25% of the total cost of the power plant [55] and was assumed to be constant every year. The maintenance cost, M_C was assumed to be 1.5% of the total cost of the PV power plant [56].

Table 4.2 contains the information regarding the inputs used in the economic analysis.

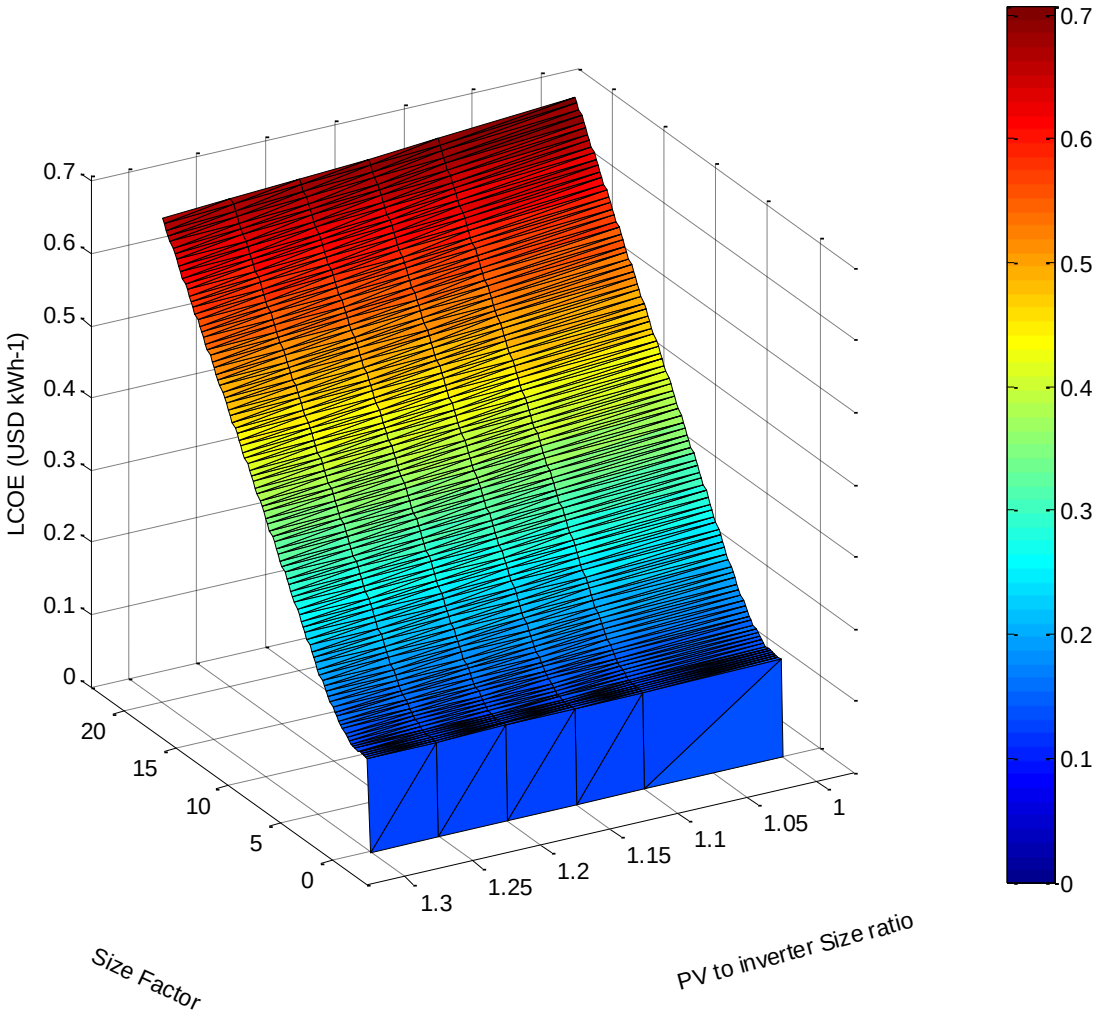


Figure 4.12 Effect of variation in Size Factor and PV to inverter size ratio on LCOE of the system

Table 4.2 Inputs used for economic analysis

C_{PV}	C_I	i	C_{GE}
USD kW^{-1}	USD kW^{-1}	%	USD kW^{-1}
700	200	15	0.22

4.2.4. Determination of Feasible Size Factor for Excess Electricity Generation Scenario

Two criteria were selected to find a feasible Size Factor in which the university still benefits economically even though the system produces excess electricity . The first criteria was that the electricity consumed at all the Size Factors from 1 to 20 in steps of 0.2 were calculated and normalized with respect to the electricity consumed by the campus at the Maximum Size Factor in consideration. The PV electricity consumption on the campus became almost constant around after the Size Factor of 5. The $LCOE$ was normalized with respect to the current grid electricity of 0.24 USD kWh^{-1}. Figure 4.13 shows the plot for normalized $LCOE$ and Normalized Excess Electricity Generated and Consumed.

It can be observed from Figure 4.13 that the Normalized Excess Electricity being generated and consumed increases linearly initially with the increase in Size Factor from 1 up to a Size Factor of 1.6 and then asymptotically approaches a value of around 0.9 until a Size Factor of 6.2. The reason to select the maximum Size Factor as 6.2 was that it is the Size Factor around which the $LCOE$ becomes equal to the grid cost of electricity and in any case, any value of Size Factor beyond 6.2 would therefore not be considered. The normalized $LCOE$ also shows an increasing trend with the increase in Size Factor and is maximum around the Size Factor of 6.2. It can also be observed that after a Size Factor of around 4.8, the electricity consumption does not increase significantly but the $LCOE$ still rises, so a Size Factor of 4.8 becomes the Maximum Feasible Size Factor.

The second criteria was based on the first criteria such that the percentage of electricity dumped at all the Size Factors was obtained and was normalized considering the Maximum Feasible Size Factor of 4.8 for the generation of excess electricity and plotted with the Normalized $LCOE$ to find the Nominal Size factor for dumping electricity. Figure 4.14 reveals the Normalized Dumped Electricity and Normalized $LCOE$ with respect to varying Size Factor.

It can be observed from the Figure 4.14 that the Normalized $LCOE$ does not increase significantly within the range of Size Factor of 1 to 4.8 and stays approximately 20% below the grid cost of electricity. The oversizing of the system is now dependent on the investor to the project that how much electricity he or she is willing to dump. If for instance, it is the investor's decision to dump around 44% of the generated electricity, then a Size Factor of around 3 will be the feasible Size Factor for excess electricity generation.

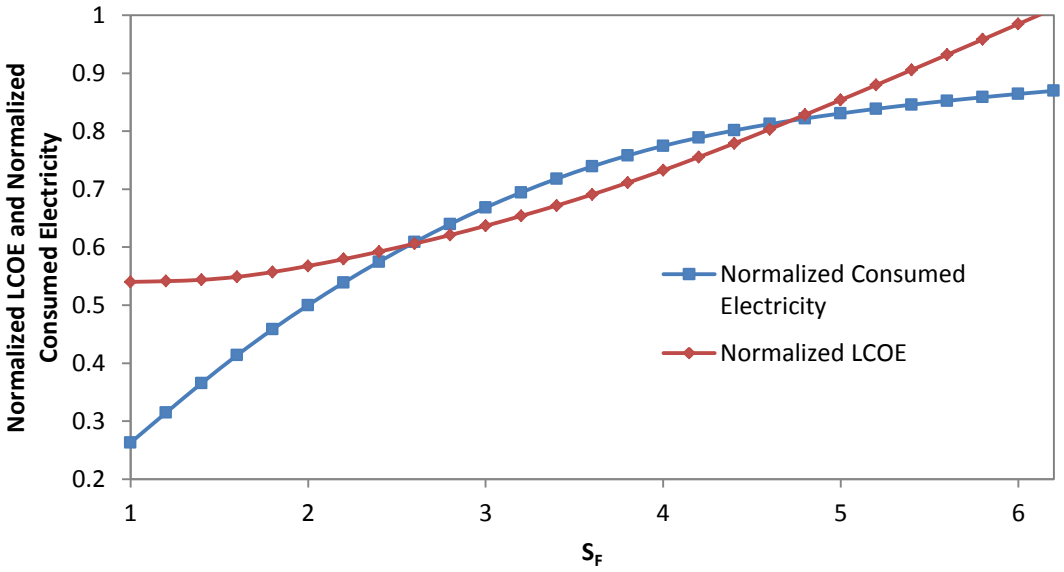


Figure 4.13 Trend Between Normalized Excess Electricity Generated and Consumed and Normalized LCOE with respect to varying Size Factor

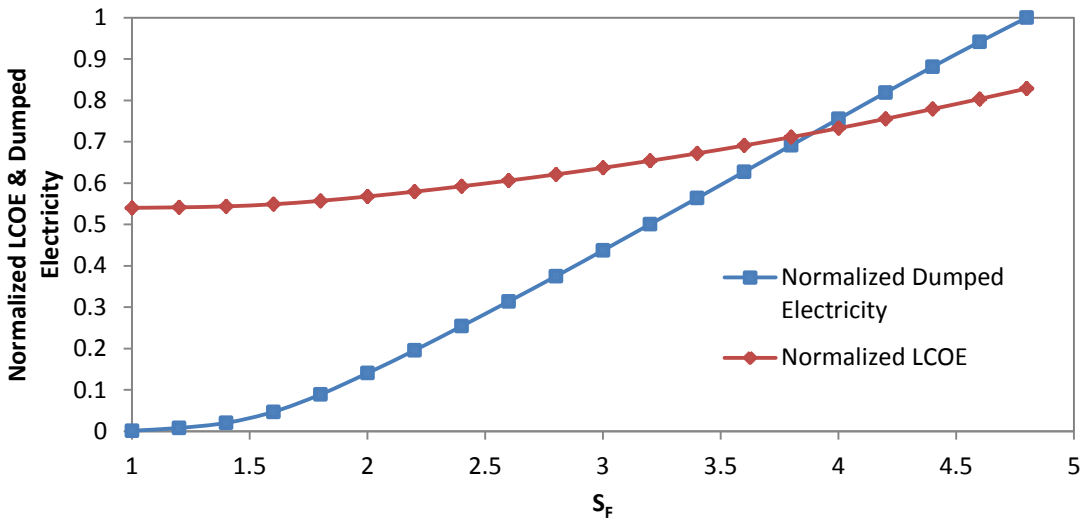


Figure 4.14 Normalized Dumped Electricity and LCOE with varying Size Factor

To further elaborate about sizing, Figure 4.15, in continuation with Figure 4.14 is presented which reflects another important point. It shows the normalized NPV with respect to the maximum NPV that can be achieved by varying Size Factors. Furthermore, it also includes the annual economic benefits, normalized with respect to the maximum economic benefit that can be achieved by varying Size Factors, in terms of electricity consumption. It can be observed from the Figure 3.15 that the maximum NPV and maximum annual economic benefits both occur at the Size Factor of around 3. So it can be stated that, dependent upon the METU NCC electricity demand, grid cost of electricity and solar resource data and various other factors, a Size Factor of 3 may be the best if the investor is willing to give free electricity to the grid. In that case, the university will be generating around 44% of excess electricity with respect to the maximum allowable excess electricity generation if $LCOE$ is desired to be around the grid cost of electricity. The Size Factor of 3 may also benefit the campus in the future, when the electricity demand increases or if carbon taxes are incorporated in North Cyprus.

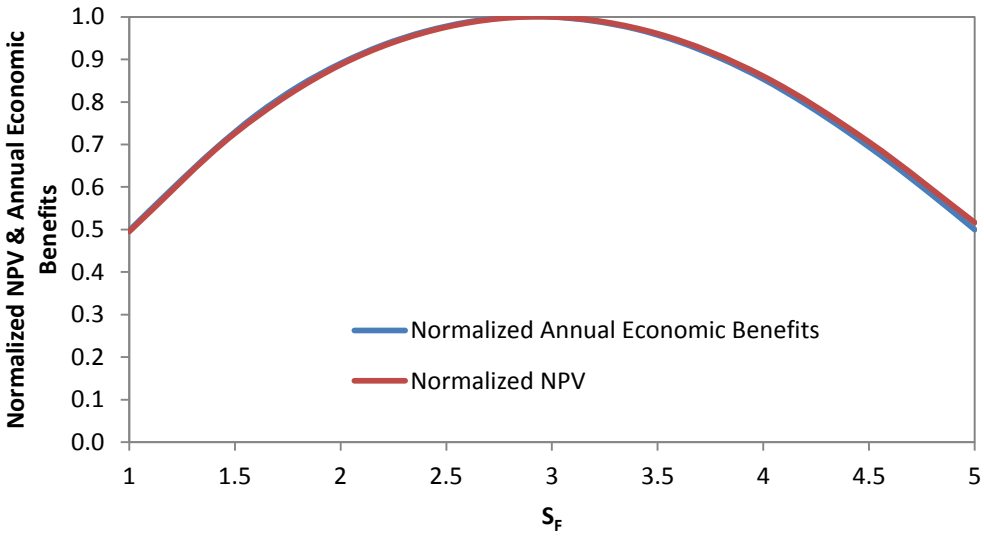


Figure 4.15 Normalized NPV and Normalized Annual Economic Benefits for METU NCC with respect to varying Size Factor

4.3. Orientation of the PV Panels

The output of a PV panel can be varied by changing the tilt angle of the PV panel. To maximize the output of the PV power plant, the Solar Fraction, f_s was increased by varying the Surface Azimuth γ_s and the tilt angle, β at the nominal design area, A_N and PV to inverter size ratio of 1.2. Figure 4.16 shows the range of optimum orientation of the PV panels to maximize the level of PV penetration to meet the electricity demand of the campus.

It can be observed from the Figure 4.16 that variation in γ_s does not significantly affect the value of f_s. The best orientation of PV panels lie between the range of 15° to 30° for β, with the γ_s as 0°. It can also be observed that even if the orientation of the PV panels is 10% different from the range of tilt angle specified, the value of f_s is not significantly altered as the value of f_s just varied between 13 and 13.5% for this case.

It can thus be concluded from the orientation point of view that it does not matter much if the tilt of the PV panels varies between 15° to 30° or even 10% more or less and the PV power plant will produce almost the same amount of electricity and providing approximately the same

level of penetration. So, METU NCC may just deploy PV panels with fixed orientation between the specified ranges.

4.4. Economic Analysis for METU NCC

The cost analysis of the PV system was calculated for three different scenarios:

1) Assuming no soft costs; i.e. minimum capital
2) Soft costs included in the capital cost, i.e. maximum capital costs
3) Average of the maximum and minimum capital costs

NPV for the power plant was calculated by using Equation (32). Table 4.3 shows the NPV calculations for the PV power plant while considering no soft costs. It can be observed in the results that the payback period of the proposed power plant, considering no excess electricity generation and no soft costs, is around 4 years which is an economically feasible result.

The second case was considered by taking the maximum cost, including the soft costs as 60% of the total capital cost of the power plant [20] and the NPV was calculated. The results presented in Table 4.4 reflect the NPV of the power plant including the soft costs. It can be observed from the results that the payback period of the power plant changed to 7 years, which also is a feasible result, considering the lifetime of the power plant.

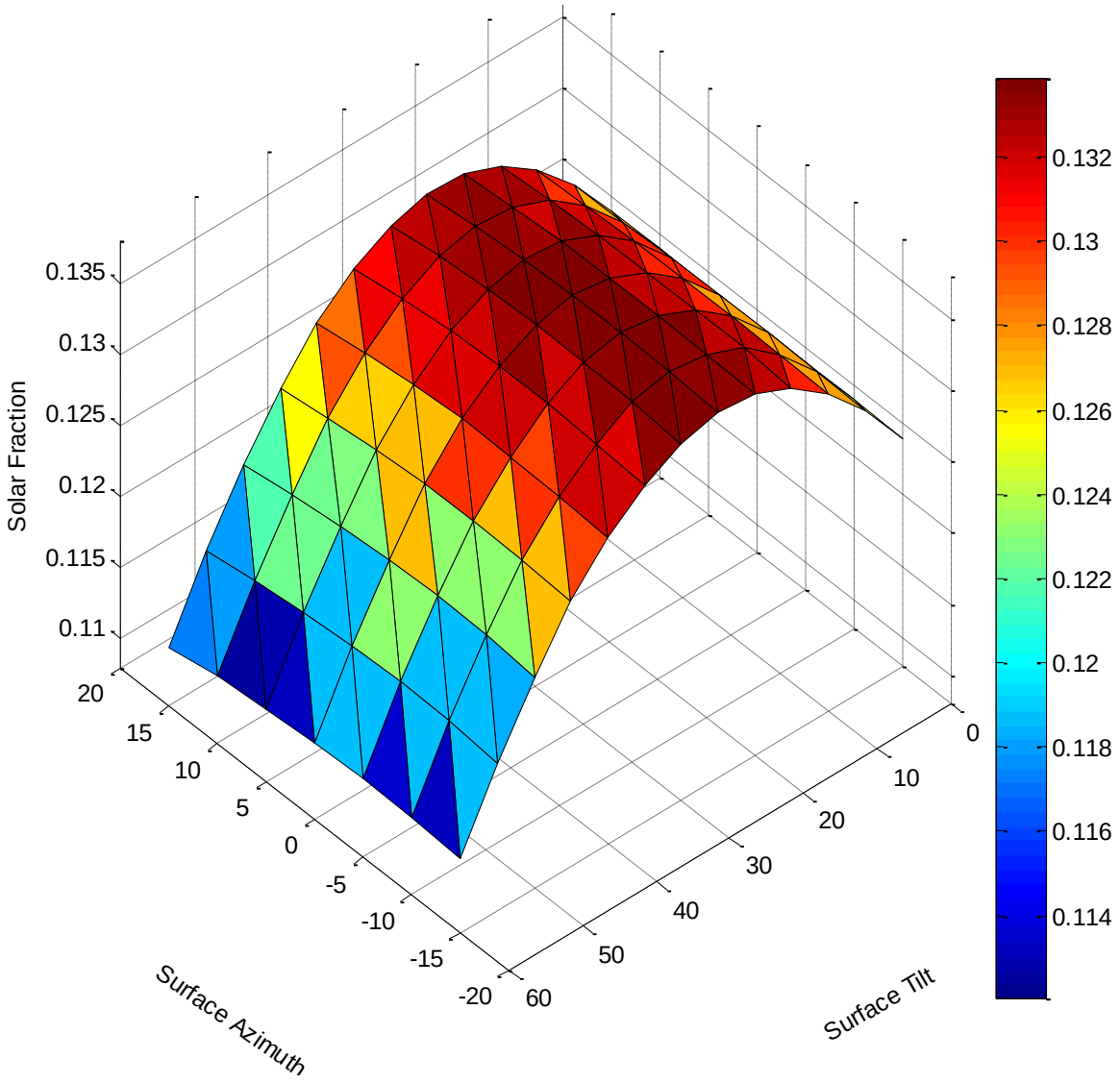


Figure 4.16 Best Orientation of PV Panels, based on Surface Azimuth and Tilt Angle

The third case considered was the average of the minimum and maximum costs. Table 4.5 shows the results obtained by using the average cost. The results show that when the average capital costs are considered, the payback period of the PV power plant becomes 5 years. Overall, it can be stated that even considering the maximum costs, the economic analysis performed yields promising results for METU NCC and the university can achieve a significant decrease in electricity bills.

Table 4.3 NPV Calculations for the PV power plant assuming no soft costs, minimum cost of the system

y	C_{NEB}	f	Present Value
-	USD	-	USD
0	-623,943	1	-623,943
1	257,460	0.87	-400,064
2	257,460	0.76	-205,388
3	257,460	0.66	-36,103
4	257,460	0.57	111,100
5	257,460	0.50	239,104
6	257,460	0.43	350,411
7	257,460	0.38	447,200
8	257,460	0.33	531,364
9	257,460	0.28	604,550
10	257,460	0.25	668,190
11	257,460	0.21	723,530
12	257,460	0.19	771,651
13	257,460	0.16	813,495
14	257,460	0.14	849,882
15	257,460	0.12	881,522
16	257,460	0.11	909,036
17	257,460	0.09	932,960
18	257,460	0.08	953,765
19	257,460	0.07	971,855
20	257,460	0.06	987,586
Total Net Present Worth			987,586

For the economic analysis, the $LCOE$ was also calculated for the project assuming no soft costs, with soft costs and the average of the two. The calculations for $LCOE$ for the PV power plant, without soft costs, at a Size Factor of 1 yielded a feasible result of 0.10 USD kWh^{-1} which is also consistent with the costs presented in [20]. For the analysis where soft costs were included, the $LCOE$ of the system became 0.16 USD kWh^{-1} while for the average of the two costs, the $LCOE$ was found to be 0.13 USD kWh^{-1}.

Table 4.4 NPV Calculations for the PV power plant assuming soft costs, maximum cost of the system

y	**C_{NEB}**	**f**	**Present Value**
-	**USD**	**-**	**USD**
0	-998,309	1	-998,309
1	250,909	0.87	-780,127
2	250,909	0.76	-590,404
3	250,909	0.66	-425,427
4	250,909	0.57	-281,969
5	250,909	0.50	-157,223
6	250,909	0.43	-48,749
7	250,909	0.38	45,577
8	250,909	0.33	127,600
9	250,909	0.28	198,924
10	250,909	0.25	260,945
11	250,909	0.21	314,876
12	250,909	0.19	361,772
13	250,909	0.16	402,552
14	250,909	0.14	438,013
15	250,909	0.12	468,848
16	250,909	0.11	495,661
17	250,909	0.09	518,977
18	250,909	0.08	539,252
19	250,909	0.07	556,882
20	250,909	0.06	572,213
Total Net Present Worth			572,213

A sensitivity analysis was performed by varying the interest rate, i, and the effect was observed on the total NPV of the PV power plant. The Size Factor selected was 1 for this analysis and the PV size to inverter size is 1.2. Figure 4.17 shows the results obtained from the sensitivity analysis. It can be observed from the results that as the interest rate increases, the total NPV reduces. This happens because as the interest rate increases, the time value of money decreases and the NPV decreases. A greater interest rate corresponds to more inflation and thus the total NPV of the project decreases.

Table 4.5 NPV Calculations for the PV power plant assuming average of the maximum and minimum costs

y	**C_{NEB}**	**f**	**Present Value**
-	**USD**	**-**	**USD**
0	-811,126	1	-811,126
1	254,185	0.87	-590,096
2	254,185	0.76	-397,896
3	254,185	0.66	-230,765
4	254,185	0.57	-85,434
5	254,185	0.50	40,940
6	254,185	0.43	150,831
7	254,185	0.38	246,389
8	254,185	0.33	329,482
9	254,185	0.28	401,737
10	254,185	0.25	464,568
11	254,185	0.21	519,203
12	254,185	0.19	566,712
13	254,185	0.16	608,024
14	254,185	0.14	643,947
15	254,185	0.12	675,185
16	254,185	0.11	702,349
17	254,185	0.09	725,969
18	254,185	0.08	746,508
19	254,185	0.07	764,369
20	254,185	0.06	779,899
Total Net Present Worth			779,899

A sensitivity analysis with respect to Size Factor and interest rate was also performed for the NPV of the PV power plant. The results from the sensitivity analysis are presented in Figure 4.18. It can be observed from the results that as the Size Factor increases, the NPV decreases. It can also be observed that, on different values of interest rate for each Size Factor, the value of NPV is decreasing. The reason of decrease in NPV due to increase in Size Factor is that, as the Size Factor increases, the system size increases which consequently leads to increase in the capital cost and the electricity produced by the system. However the electricity produced is not consumed on the campus and it does not generate much revenue compared to the increase in capital cost which ultimately leads to reduction in NPV.

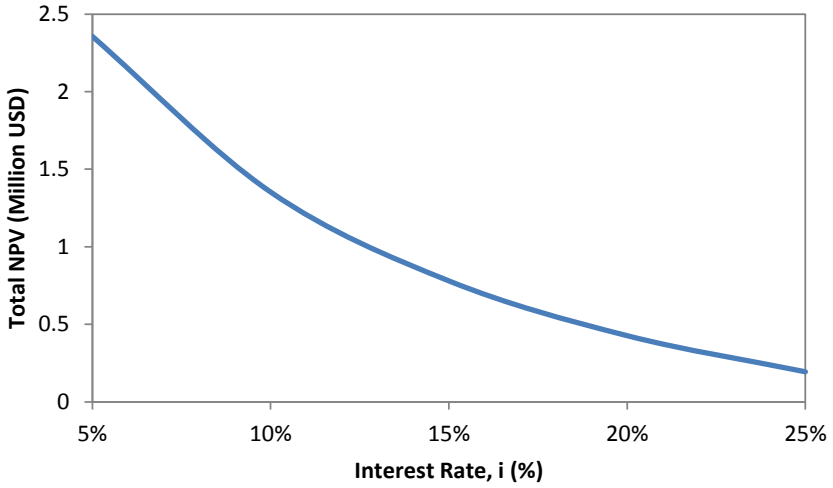


Figure 4.17 Sensitivity Analysis for NPV by varying Interest Rate

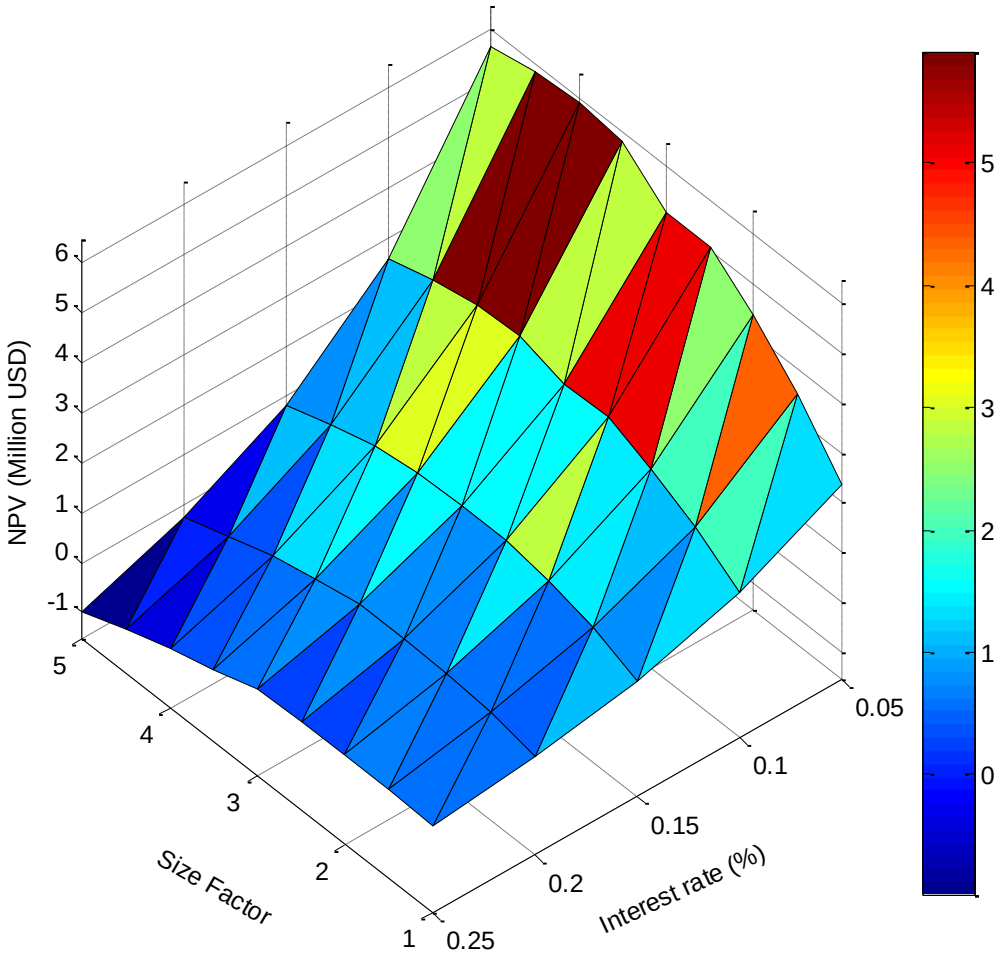


Figure 4.18 Sensitivity Analysis for NPV by varying Size Factor and Interest Rate

4.5. Ecological Assessment of the PV power plant at METU NCC

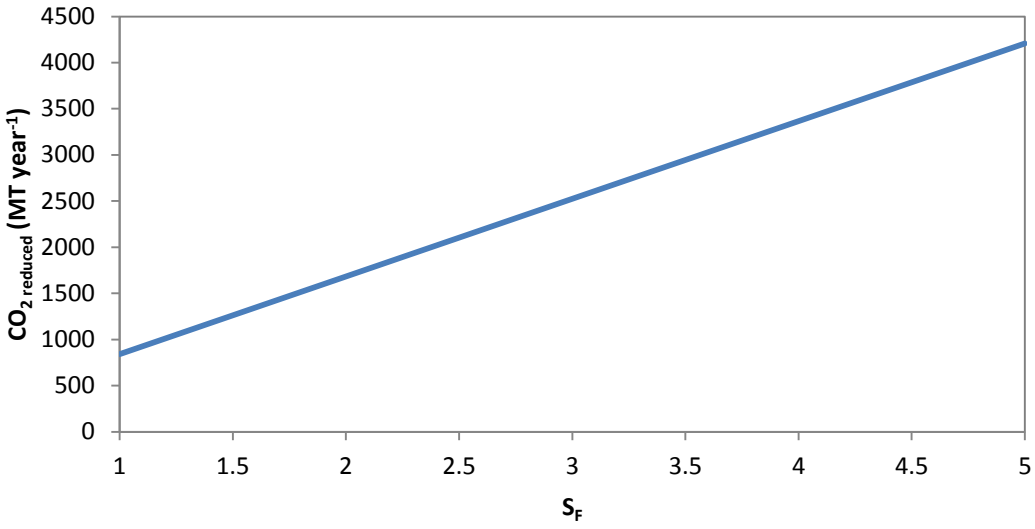


Figure 4.19 Estimated reduction in CO_2 every year due to change in Size Factor

The CO_2 emission rates for oil as stated by EPA are approximately 758.41 kg MWh^{-1} [62]. This emission rate was used to obtain the CO_2 emissions reduced at METU NCC by substituting the electricity produced by Fuel Oil No.6 in KIB-TEK. The analysis is based on electricity generated rather than PV electricity consumed on the campus because even if the electricity generated by the solar PV power plant is not consumed on campus, it will be fed to the grid for free and it will reduce the electricity generation from Fuel Oil No.6. The assumption made is that the amount of emission rate provided for oil was taken the same for Fuel Oil No.6. The Size Factor taken was 1 and the PV to inverter size ratio was taken as 1.2. The results indicate that the METU NCC can contribute to a reduction of 841 MT $year^{-1}$. As the Size Factor was increased from 1 to 5, the reduction in CO_2 also increased linearly. Figure 3.19 indicates the reduction in CO_2 with respect to Size Factor.

As the Size factor increases, the reduction in CO_2 will increase due to the fact that a greater Size Factor corresponds to a greater PV area and hence electricity generation. So the more electricity is generated due to solar PV, the more CO_2 will be reduced. At a Size Factor of 5, approximately 4200 MT of CO_2 can be saved ever year.

CHAPTER 5

PV POWER PLANT AT METU NCC

As described earlier, the university administration of METU NCC has obtained a license for a 1 MW PV power plant at METU NCC, which corresponds to an area of 9000 m^2 and Size Factor of 1.85. The design of the power plant may partly dependent upon findings from this research. This chapter presents an overview about the comparison between the 1 MW power plant and the power plant at a Size Factor of 1, which corresponds to a rated power of 0.72 MW and area of 4871 m^2.

5.1 Electricity demand and generation profile

The electricity consumption and electricity generation from solar PV at METU NCC is presented in Figure 5.1. The plot indicates the amount of electricity generated from a solar PV power plant with 0 Size Factor to around the Maximum Feasible Size Factor of 4.8, which was explained earlier in section 4.2.4. It can be observed from Figure 5.1 that a PV power plant of 1 MW, having a Size Factor of 1.85, at METU NCC will not overproduce much electricity and almost all the electricity generated will be consumed on campus.

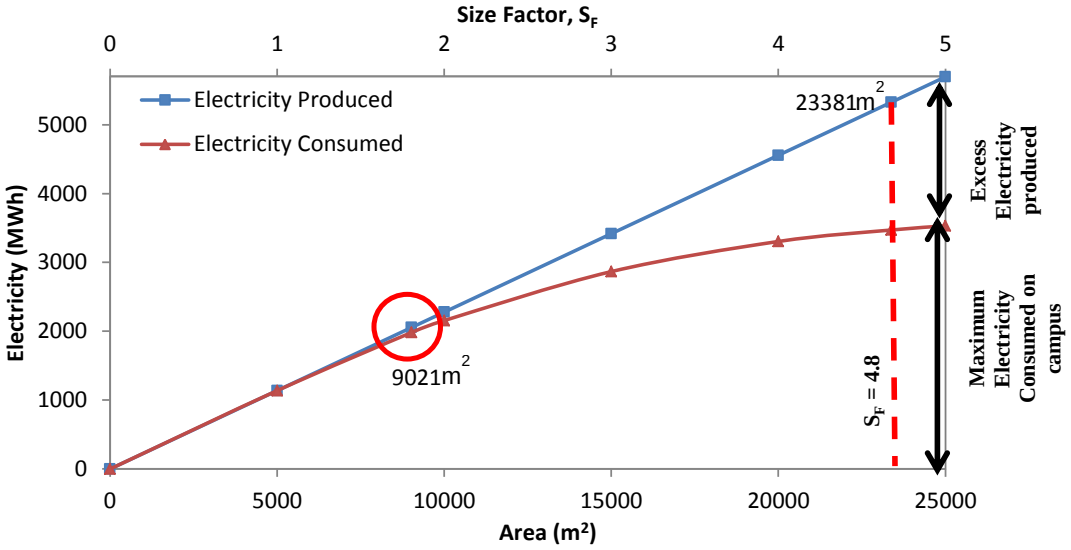


Figure 5.1 Electricity Generation and Consumption at METU NCC for 1 MW power plant, up to 3.7 MW

As the capacity of the PV power plant is increased from 1 MW up to 3.7 MW, the amount of electricity generated in excess increases. While much portion of the electricity is still consumed of the campus, though more is fed to the electricity grid for free.

As discussed in Chapter 4, the Nominal Design Capacity for METU NCC using solar radiation data measured at METU NCC was obtained as 0.72 MW, which corresponded to an area of 4871 m^2. The electricity demand and generation profile for METU NCC around the nominal design time was analyzed with the electricity generation profile of a 1 MW power having an area of around 9000 m^2, with a Size Factor of around 1.85. The PV to inverter size ratio was taken as 1.2. The results are presented in Figure 5.2.

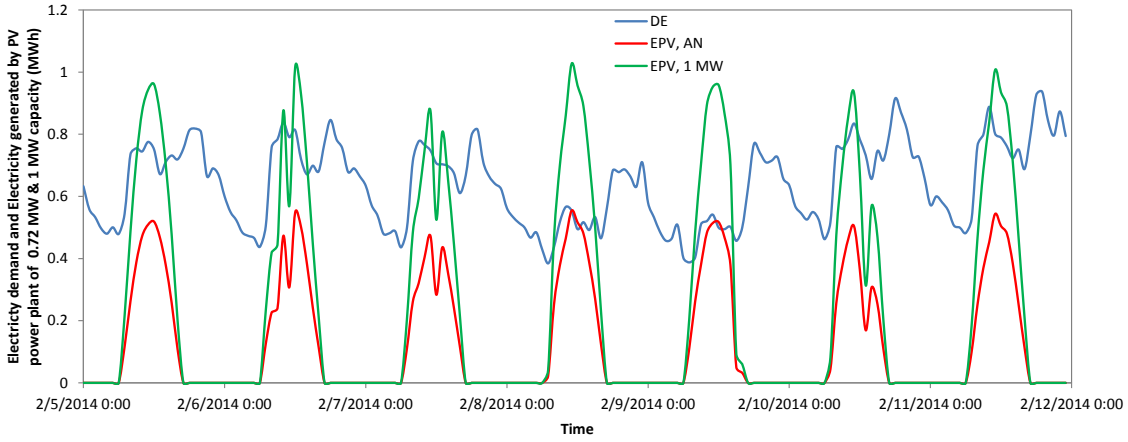


Figure 5.2 Electricity Demand of METU NCC and Electricity generated by a PV power plant having area equal to Nominal Design Area and 1 MW PV power plant

The results indicate that when the area is equal to nominal design area, all the electricity being produced by PV panels will be consumed on campus and as the capacity of the power plant is increased beyond the nominal capacity, excess electricity is being generated and is being fed to the grid for free. However, the results in Chapter 4 indicate that a Size Factor of around 4.8, which corresponds to PV area of around 23,381 m^2 and a rated capacity of around 3.4 MW may also be feasible since the LCOE is kept below the grid cost of electricity even though the campus is generating excess electricity. Therefore a 1 MW PV system corresponding to a Size Factor of 1.85 falls well within the acceptable range. Furthermore, if the campus is willing to build a slightly oversized PV power plant, it will benefit the campus in the future when the number of students and the electricity consumption of the campus increases. To elaborate the

sizing further and to visualize the electricity demand and electricity generation using solar PV patterns, Figure 5.3 presents a plot of 14 characteristic days of summer, from June 1st to June 14th 2013.

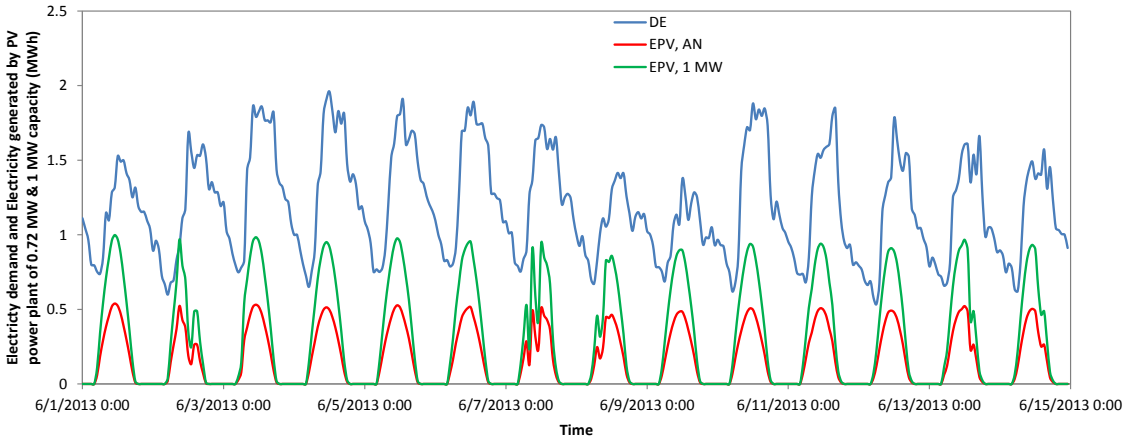


Figure 5.3 Electricity Demand and generation at METU NCC using Solar PV at a Size Factor of 1 and 1.85 for the period 1st June 2013 to 14th June 2013

It can be observed from the plot that even if the Size Factor is 1.85, the electricity generated by the PV power plant at METU NCC is being consumed at the campus and no free electricity is being given to the utility company and the university is being benefitted. Furthermore, this also confirms the idea of an oversized system in the range up to 4.8 that the electricity generated by the PV power plant will be consumed on the campus, without generating excess electricity for most of the time. An oversized system will generate excess electricity at least on the nominal design time and other occasions in the year when the electricity demand is lower than the electricity generated.

The period around which the maximum electricity demand occurred in the campus was also analyzed to investigate whether the 1 MW PV power plant at METU NCC would generate excess electricity or not. The results of the parametric study are presented in Figure 5.4. It can be observed from the figure that during the period of maximum demand of the campus in the entire year, the electricity generated by both the 1 MW PV power plant and nominally size plant never exceeds the electricity demand and hence all the generated electricity will be consumed on the campus.

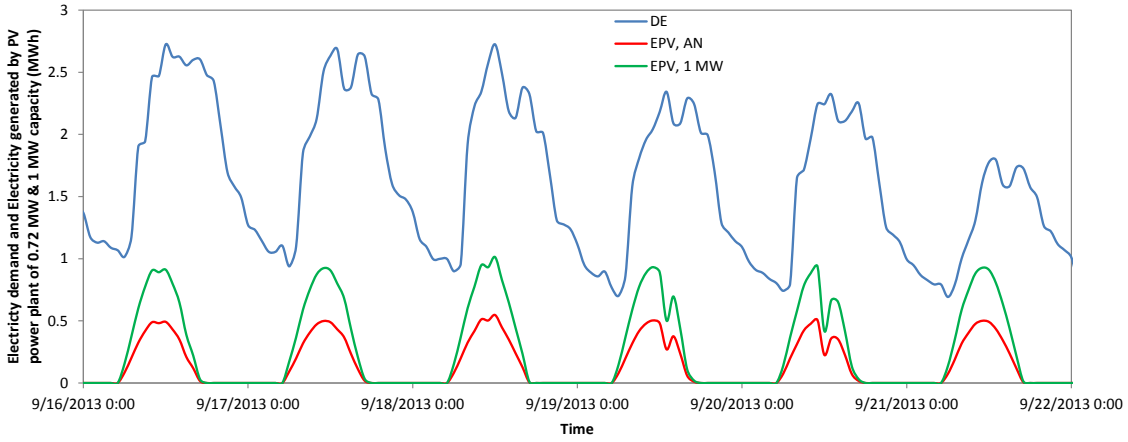


Figure 5.4 Electricity Demand and generation at METU NCC using Solar PV at a Size Factor of 1 and 1.8 for the period 15th September 2013 to 22nd September 2013

The period to from 1st December 2013 to 14th December 2013 was also investigated. This period was selected to observe the functionality and output of the power plant in winter, having low solar resources. Figure 5.5 shows the results for this study.

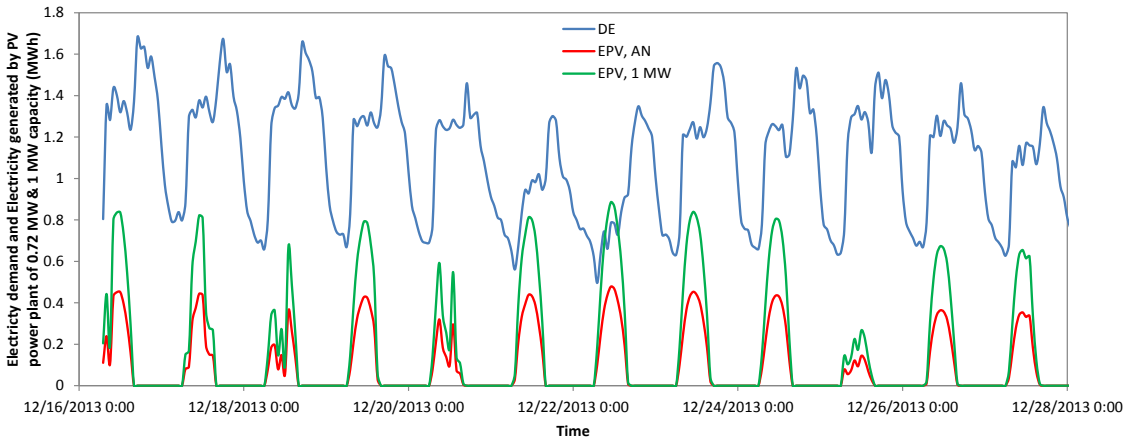


Figure 5.5 Electricity Demand and generation at METU NCC using Solar PV at a Size Factor of 1 and 1.8 for the period 15th December 2013 to 28th December 2013

It can be seen from Figure 5.5 that as the Winter period has less solar resources compared to Summer, so the 1 MW PV power plant does not produce excess electricity at most of the instances. Only a slight amount of excess electricity was generated on 22nd December 2013 around 11:00, which is due to low electricity demand as it was a Sunday and also this day, the

amount of solar resources were fair. The electricity generated however from the PV power plant with nominal capacity always generate less electricity compared to the electricity demand for this period.

5.2 Comparison of the Electricity generated and dumped by the 1 MW PV power plant at METU NCC

To quantify the amount of electricity produced in excess and consumed by installing a 1 MW PV power plant at METU NCC, the results are presented in Table 5.1.

Table 5.1 Total Electricity produced by 1 MW PV power plant at METU NCC with electricity consumption on campus and the dumped electricity to the utility grid

Month	Electricity produced by PV MWh	Electricity Consumed MWh	Electricity Dumped to the grid MWh	% Electricity Dumped %
Jun-13	218.93	216.18	2.75	1.26%
Jul-13	224.63	224.62	0.01	0.01%
Aug-13	220.49	212.80	7.70	3.49%
Sep-13	199.98	199.00	0.98	0.49%
Oct-13	208.54	204.48	4.06	1.95%
Nov-13	116.32	115.56	0.75	0.65%
Dec-13	105.22	104.15	1.07	1.01%
Jan-14	112.88	111.03	1.86	1.65%
Feb-14	153.50	138.02	15.49	10.09%
Mar-14	179.75	163.66	16.08	8.95%
Apr-14	167.75	150.08	17.67	10.53%
May-14	146.87	142.54	4.33	2.95%
Annual	2055	1982	73	3.54%

The results indicate that only 73 MWh (3.5%) of electricity will be dumped to the grid annually which is not so significant considering that most of the electricity produced by the PV power plant will be consumed on campus and a monthly maximum of around 10.5% of the total electricity produced is dumped to the utility grid, in the month of April 2014. February, March and April 2014 have the maximum percentage of electricity being dumped and the reason for this is the low electricity demand of these months. Since the electricity demand is low overall, a comparatively larger portion of electricity is being dumped to the grid for free, since the PV power plant is slightly oversized compared to the nominal design size.

5.3 Economic Analysis of 1 MW PV power plant at METU NCC

The economic analysis of 1 MW PV project at METU NCC was also calculated and Table 5.2 indicates the result from the analysis. The analysis was performed considering the average of the maximum and minimum costs, as stated in Chapter 4 and it can be seen that the installation of a 1 MW PV power plant at METU NCC seems to achieve fruitful results. The payback period of the power plant is around 5 years, which is feasible and in the light of the results from Table 5.1 it can be stated that most of the electricity generated by using 1 MW PV power plant at METU NCC will be consumed on the campus.

Table 5.2 NPV calculations for 1 MW PV power plant at METU NCC using the average of maximum and minimum costs

y	**C_{NEB}**	**f**	**Present Value**
-	**USD**	**-**	**USD**
0	-1,502,222	1	-1,502,222
1	453,384	0.87	-1,107,975
2	453,384	0.76	-765,152
3	453,384	0.66	-467,045
4	453,384	0.57	-207,821
5	453,384	0.50	17,590
6	453,384	0.43	213,601
7	453,384	0.38	384,045
8	453,384	0.33	532,256
9	453,384	0.28	661,136
10	453,384	0.25	773,206
11	453,384	0.21	870,658
12	453,384	0.19	955,398
13	453,384	0.16	1,029,086
14	453,384	0.14	1,093,162
15	453,384	0.12	1,148,880
16	453,384	0.11	1,197,331
17	453,384	0.09	1,239,462
18	453,384	0.08	1,276,098
19	453,384	0.07	1,307,955
20	453,384	0.06	1,335,657
Total Net Present Worth			1,335,657

NPV of the project was also calculated for the maximum and minimum cost scenarios as presented in Section 3.2.4. The results are presented in Table 5.3 and Table 5.4 respectively. The payback period of the PV power plant reached a maximum of around 7 years for the maximum cost case and a minimum of around 4 years for the minimum cost scenario. $LCOE$ was also calculated for the 1 MW PV power plant and it was found to be 0.13 USD kWh^{-1}, 0.10 USD kWh^{-1} and 0.17 USD kWh^{-1} respectively which shows that the $LCOE$ does not increase much for the maximum cost scenario and it remains still below the current grid cost of electricity of 0.24 USD kWh^{-1}, suggesting the feasibility of the project.

Table 5.3 NPV calculations for 1 MW PV power plant at METU NCC considering maximum cost scenario

y	**C_{NEB}**	**f**	**Present Value**
-	**USD**	**-**	**USD**
0	-1,848,889	1	-1,848,889
1	447,317	0.87	-1,459,918
2	447,317	0.76	-1,121,682
3	447,317	0.66	-827,563
4	447,317	0.57	-571,808
5	447,317	0.50	-349,413
6	447,317	0.43	-156,025
7	447,317	0.38	12,138
8	447,317	0.33	158,367
9	447,317	0.28	285,522
10	447,317	0.25	396,092
11	447,317	0.21	492,240
12	447,317	0.19	575,847
13	447,317	0.16	648,548
14	447,317	0.14	711,767
15	447,317	0.12	766,740
16	447,317	0.11	814,542
17	447,317	0.09	856,109
18	447,317	0.08	892,255
19	447,317	0.07	923,686
20	447,317	0.06	951,017
Total Net Present Worth			951,017

Table 5.4 NPV calculations for 1 MW PV power plant at METU NCC considering minimum cost scenario

y	**C_{NEB}**	**f**	**Present Value**
-	**USD**	**-**	**USD**
0	-1,155,556	1	-1,155,556
1	459,450	0.87	-756,033
2	459,450	0.76	-408,623
3	459,450	0.66	-106,527
4	459,450	0.57	156,165
5	459,450	0.50	384,594
6	459,450	0.43	583,227
7	459,450	0.38	755,951
8	459,450	0.33	906,146
9	459,450	0.28	1,036,751
10	459,450	0.25	1,150,320
11	459,450	0.21	1,249,076
12	459,450	0.19	1,334,950
13	459,450	0.16	1,409,624
14	459,450	0.14	1,474,557
15	459,450	0.12	1,531,021
16	459,450	0.11	1,580,120
17	459,450	0.09	1,622,815
18	459,450	0.08	1,659,941
19	459,450	0.07	1,692,224
20	459,450	0.06	1,720,297
Total Net Present Worth			1,720,297

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Solar photovoltaic (PV) seems to have a promising future with the manufacturing cost going down during the past few years. North Cyprus, having good solar resource potential, can benefit by using PV to generate electricity, in terms of sustainability and economics, as explained in detail in the introduction and literature review section. There are several methods to design PV systems but there exists no method for sizing that directly addresses the electricity demand of a location, with unidirectional metering. First, a new methodology is developed in the thesis, based on the hourly solar resources and electricity demand of a location focused on unidirectional metering.

The methodology developed is general in application and can be applied anywhere in the world, with similar input data. Where the methodology defines a new sizing method, it also addresses the electricity demand and solar resource data handling. The methodology also incorporates the use of an energetic model, which is already present in the literature, to estimate the efficiency of PV panels with respect to meteorological conditions. The model was also verified using measured data on a Solar PV power plant at Serhatköy, North Cyprus both in terms of cell efficiency and power output of the PV panels. The model yielded results that are in good agreement with the measured data. Measured solar resource data for the entire year was also obtained from the website of PV power plant at Serhatköy, North Cyprus and the measured solar resource data at METU NCC was compared against it. The data seemed to have good for most of the months, with good agreement in months from July 2013 to March 2014 and differed a bit more in April 2014 and May 2014, with METU NCC having low measured solar resources.

While sizing the PV panels, the data measured at METU NCC was compared by using synthetic TMY2 and measured data at Serhatköy, for observing if different results arise by using different solar resource data sets. It was observed that there was not much difference in the size of PV panels achieved by the three different data sets used. It was concluded that if there is some faulty or erroneous solar resource data measured, it may be substituted by synthetic TMY2 data.

However, it was also concluded that this may be specific for METU NCC, depending upon the electricity demand profile and before generalization; it should be tested for other locations as well.

For the PV power plant to generate as much electricity as the electricity demand of METU NCC for one year, it was observed that an a PV panel area around 40000 m^2 would be sufficient to generate the required amount of electricity. However, it was concluded that there is a limit to which the generated electricity would be utilized on the campus and much of the generated electricity would be fed to the grid for free, since the PV system in consideration does not incorporate any net-metering or battery backup. It was also concluded that PV can penetrate at a maximum of 13% in the electricity mix of METU NCC, if no electricity is generated in excess.

While sizing the inverter with varying Size Factor, it was observed that the $LCOE$ was lowest when a PV to inverter Size Factor of 1.3 was considered. It was also observed from the results that a Size Factor of 6.2 made the $LCOE$ equal to the current grid cost of electricity of North Cyprus. The PV system was then considered to generate excess electricity and a Size Factor of 4.8 was determined to be the Maximum Feasible Size Factor if excess electricity generation and economic benefits to METU NCC were considered. It was also observed that a Size Factor of 3 was the best feasible option, when excess electricity generation is considered, since it yielded maximum NPV and maximum economic benefits for METU NCC.

While observing the orientation of PV panels, it was concluded that it did not matter much if the tilt of the PV panels varied between 15° to 30° or even 10% greater or lower than the specified ranges and the PV power plant would produce almost the same amount of electricity and providing approximately the same level of penetration in the energy mix of METU NCC. So METU NCC may consider the installation of fixed PV panels within the range of the suggested orientation.

The economic analysis yielded satisfactory and good results. For the worst case scenario, with maximum costs considered, the payback period of the proposed power plant was found to be 7 years, which is feasible since the lifetime of the project was assumed to be 20 years. For the scenario with the average of maximum and minimum costs, it was found that the payback period of the PV power plant was 5 years and while minimum costs of the system were considered, the payback period became a minimum of 4 years. The $LCOE$ calculated for each of

the cases was found to be 0.16 USD kWh^{-1}, 0.13 USD kWh^{-1} and 0.10 USD kWh^{-1} respectively. Furthermore, the increase in interest rates also showed to affect the NPV of the system negatively when a sensitivity analysis on was performed regarding the NPV and interest rate.

The ecological assessment of the proposed PV power plant at METU NCC revealed that annually, METU NCC can contribute to lessening of 841 MT $year^{-1}$of CO_2 and thus mitigate climate change, strengthen the green campus initiative and provide motivation for other universities to follow suit.

6.2 Future Work

In this research work, the designing of PV systems with unidirectional metering is investigated and explored. Future work in this area may include designing of a PV system with net-metering and determination of an optimal Size Fraction for excess electricity generation considering a location having similar resources. This research did not include any tracking surfaces (North-South) and (East-West) tracking. Future work may also include considering tracking surfaces for maximizing the output of the power plant followed with the economic assessment. This research did not consider any battery storage and future research in this area may include considering battery backup to maximize PV penetration at a location.

The present analysis is based on 1-year historical solar resource and demand data. The work can be improved using forecasting methods and sensitivity analyses to better predict future performance and extended running what-if scenarios such as what happens to the economics if the price of electricity goes up or down (such as due to electric tie-line to Turkey that would decrease the cost of elec.), if net-metering or a feed-in tariff is implemented (change in policy).

Furthermore, future work may also include verification of this methodology with the 1 MW power plant being considered to be installed at METU NCC. In addition to that, the methodology developed may also be applied on macro level to a city and estimate the different levels of PV penetration with varying Size Factors. Future works may also include making modifications in this methodology and transforming to be applicable to STE (Solar Thermal Electric) systems for designing and sizing of such systems.

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APPENDIX A

COMPARISON OF METU NCC AND SERHATKÖY SOLAR RESOURCE DATA

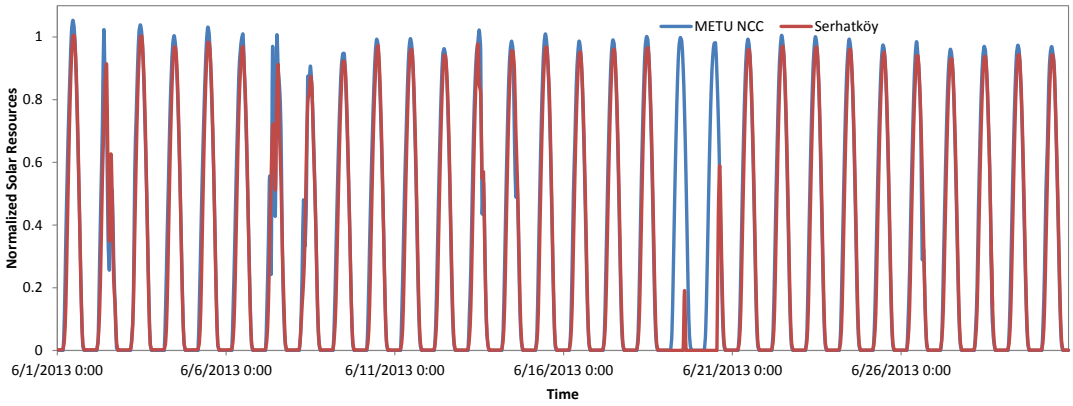


Figure A.1 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for June 2013

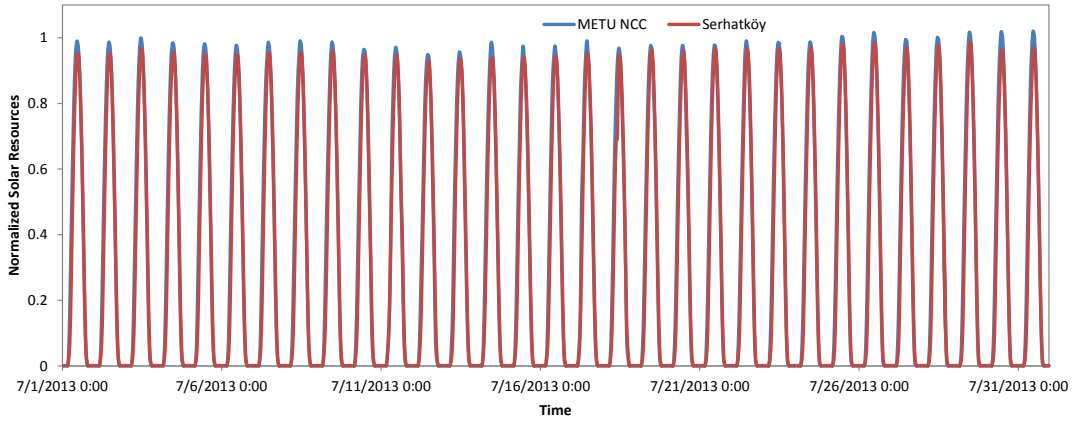


Figure A.2 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for July 2013

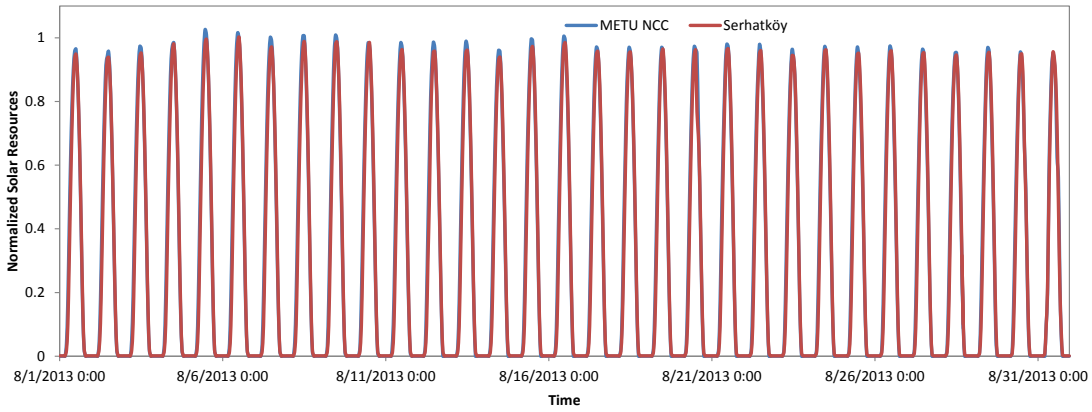


Figure A.3 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for August 2013

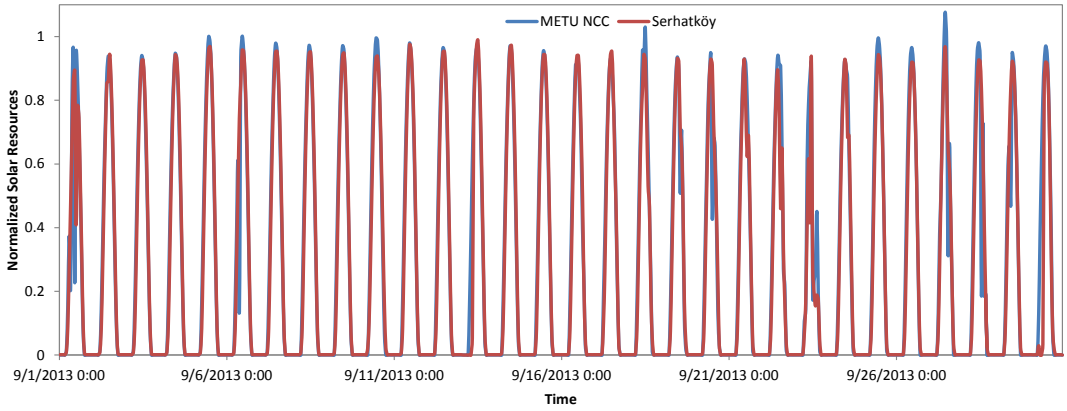


Figure A.4 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for September 2013

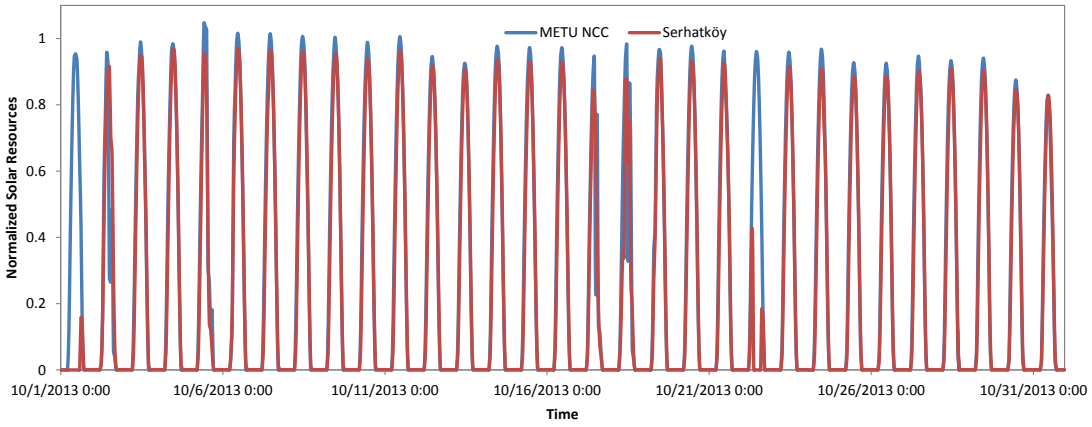


Figure A.5 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for October 2013

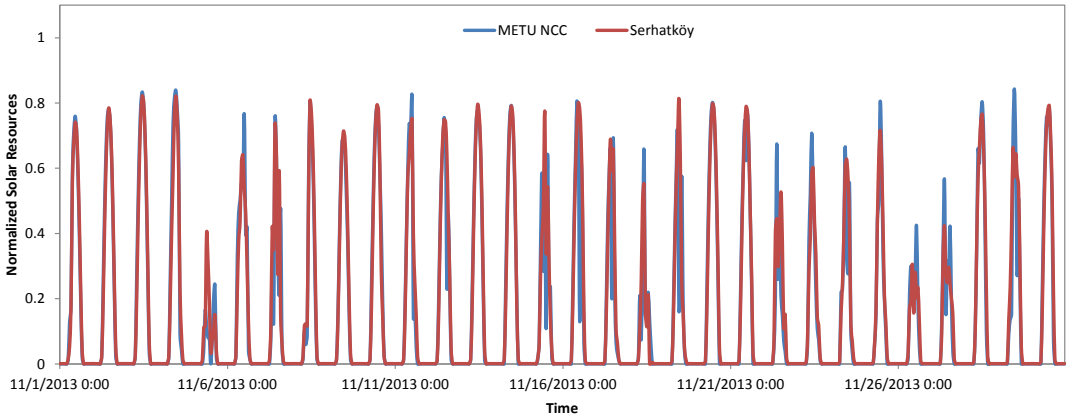


Figure A.6 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for November 2013

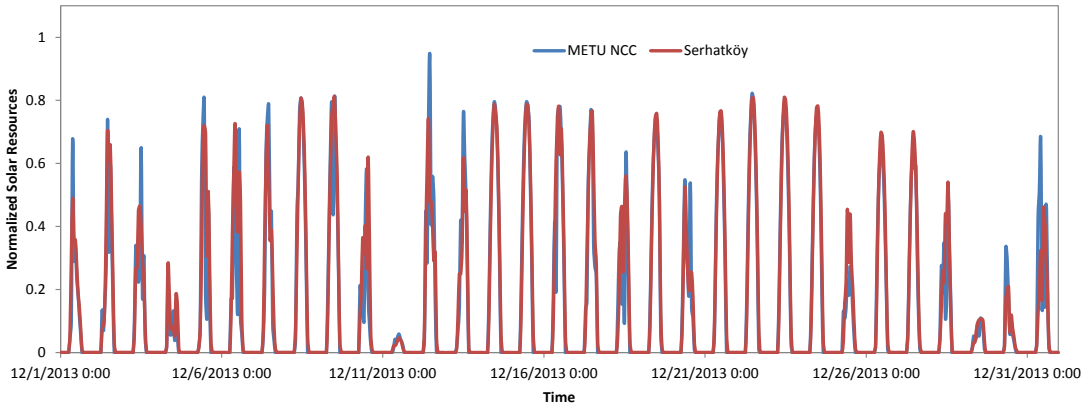


Figure A.7 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for December 2013

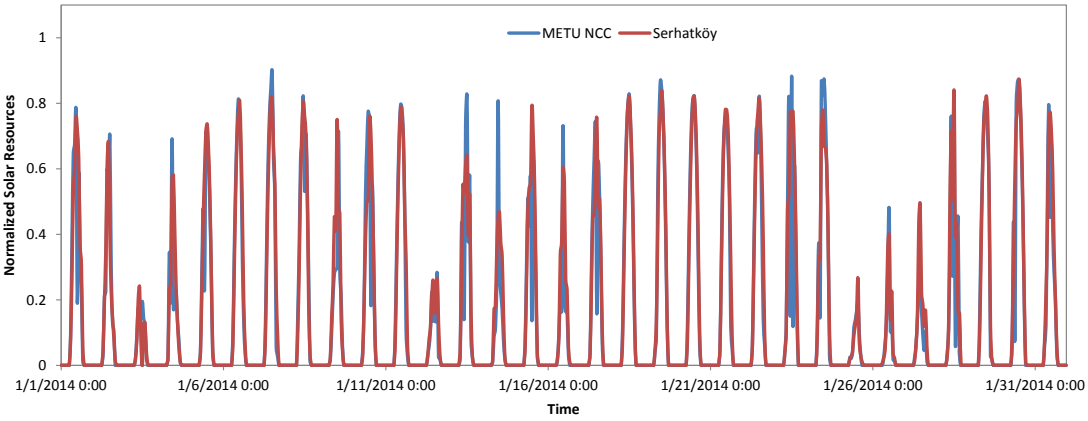


Figure A.8 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for January 2014

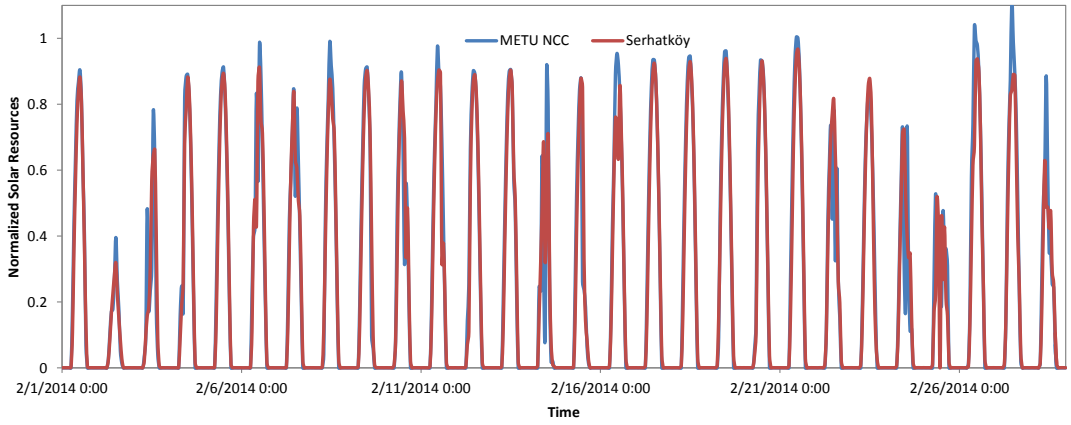


Figure A.9 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for February 2014

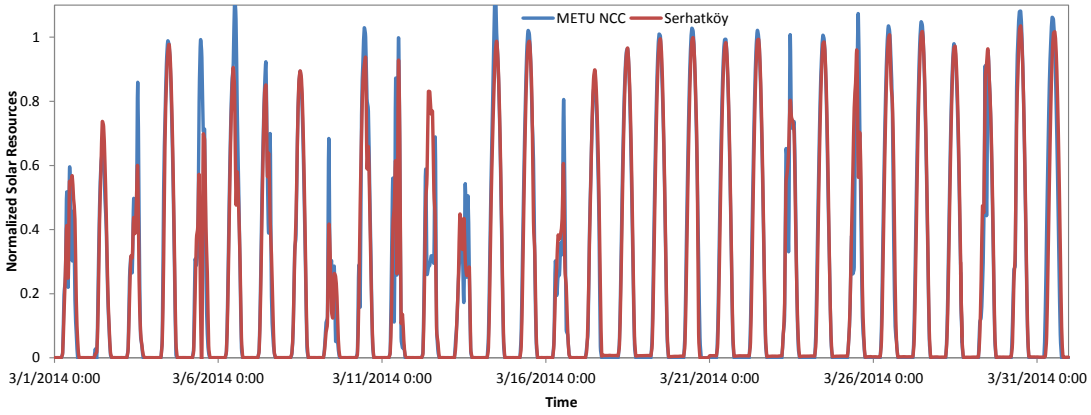


Figure A.10 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for March 2014

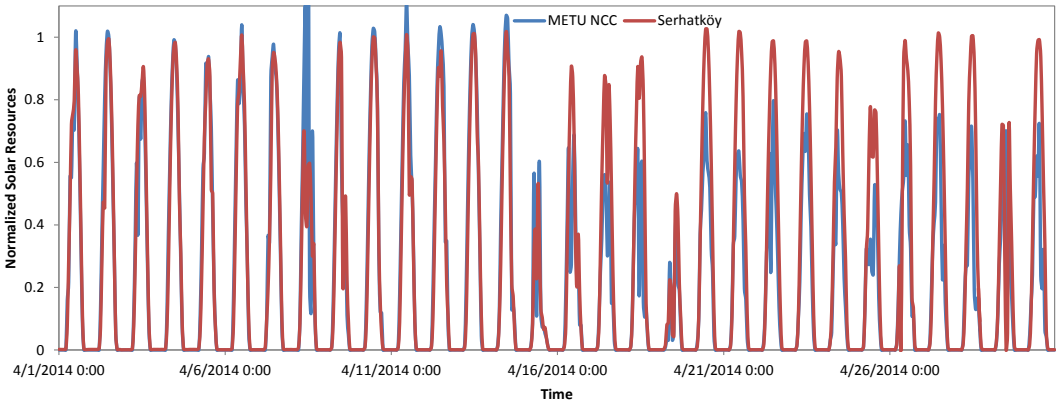


Figure A.11 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for April 2014

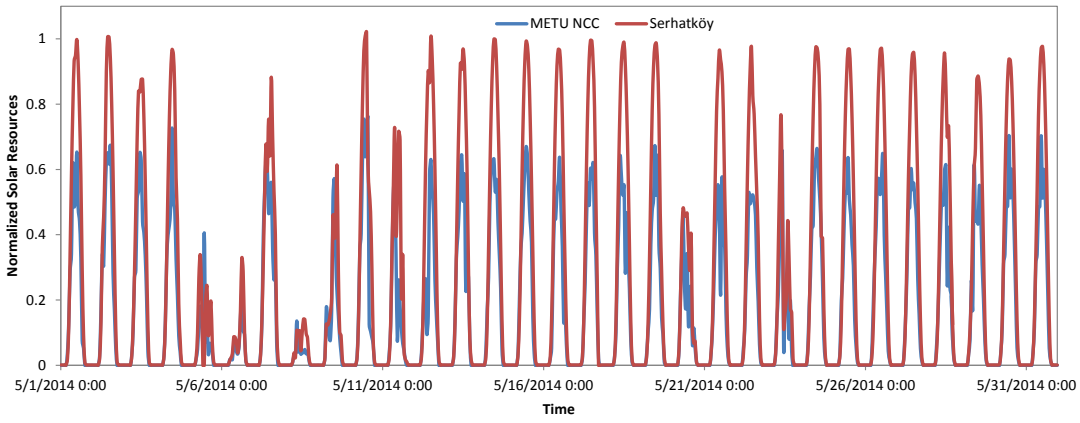


Figure A.12 Comparison between Normalized METU NCC and Serhatköy Solar Resource Data for May 2014

Table A.1 Comparison of annual solar resources between METU NCC and Serhatköy

Month	METU NCC	Serhatköy	Difference
	Wh m^{-2}	Wh m^{-2}	%
Jun-13	234,869	205,929	-14.05%
Jul-13	241,000	227,281	-6.04%
Aug-13	230,722	221,579	-4.13%
Sep-13	202,009	193,366	-4.47%
Oct-13	200,283	178,856	-11.98%
Nov-13	111,438	116,589	4.42%
Dec-13	99,227	105,537	5.98%
Jan-14	107,522	116,278	7.53%
Feb-14	147,778	142,912	-3.40%
Mar-14	180,293	178,015	-1.28%
Apr-14	163,187	191,034	14.58%
May-14	122,837	194,126	36.72%
Annual	2,041,168	2,071,502	1.46%

APPENDIX B

PARAMETERS FOR DETERMINING THE FEASIBLE SIZE FACTOR FOR EXCESS ELECTRICITY GENERATION

Table B.1 LCOE with varying S_I and S_F

LCOE (USD kWh^{-1})							LCOE (USD kWh^{-1})						
S_F \ S_I	**1**	**1.1**	**1.15**	**1.2**	**1.25**	**1.3**	S_F \ S_I	**1**	**1.1**	**1.15**	**1.2**	**1.25**	**1.3**
0	0	0	0	0	0	0	**10.2**	0.38	0.38	0.37	0.37	0.37	0.37
0.2	0.13	0.13	0.13	0.13	0.13	0.13	**10.4**	0.39	0.38	0.38	0.38	0.37	0.37
0.4	0.13	0.13	0.13	0.13	0.13	0.13	**10.6**	0.40	0.39	0.39	0.38	0.38	0.38
0.6	0.13	0.13	0.13	0.13	0.13	0.13	**10.8**	0.40	0.40	0.39	0.39	0.39	0.38
0.8	0.13	0.13	0.13	0.13	0.13	0.13	**11**	0.41	0.40	0.40	0.40	0.39	0.39
1	0.13	0.13	0.13	0.13	0.13	0.13	**11.2**	0.42	0.41	0.41	0.40	0.40	0.40
1.2	0.13	0.13	0.13	0.13	0.13	0.13	**11.4**	0.42	0.42	0.41	0.41	0.41	0.40
1.4	0.14	0.13	0.13	0.13	0.13	0.13	**11.6**	0.43	0.42	0.42	0.42	0.41	0.41
1.6	0.14	0.13	0.13	0.13	0.13	0.13	**11.8**	0.44	0.43	0.42	0.42	0.42	0.42
1.8	0.14	0.14	0.13	0.13	0.13	0.13	**12**	0.44	0.44	0.43	0.43	0.42	0.42
2	0.14	0.14	0.14	0.14	0.14	0.13	**12.2**	0.45	0.44	0.44	0.43	0.43	0.43
2.2	0.14	0.14	0.14	0.14	0.14	0.14	**12.4**	0.46	0.45	0.44	0.44	0.44	0.43
2.4	0.15	0.14	0.14	0.14	0.14	0.14	**12.6**	0.46	0.45	0.45	0.45	0.44	0.44
2.6	0.15	0.15	0.15	0.15	0.14	0.14	**12.8**	0.47	0.46	0.46	0.45	0.45	0.45
2.8	0.15	0.15	0.15	0.15	0.15	0.15	**13**	0.48	0.47	0.46	0.46	0.46	0.45
3	0.16	0.16	0.15	0.15	0.15	0.15	**13.2**	0.48	0.47	0.47	0.47	0.46	0.46
3.2	0.16	0.16	0.16	0.16	0.16	0.15	**13.4**	0.49	0.48	0.48	0.47	0.47	0.47
3.4	0.17	0.16	0.16	0.16	0.16	0.16	**13.6**	0.50	0.49	0.48	0.48	0.48	0.47
3.6	0.17	0.17	0.17	0.17	0.16	0.16	**13.8**	0.50	0.49	0.49	0.49	0.48	0.48
3.8	0.18	0.17	0.17	0.17	0.17	0.17	**14**	0.51	0.50	0.50	0.49	0.49	0.48
4	0.18	0.18	0.18	0.18	0.17	0.17	**14.2**	0.52	0.51	0.50	0.50	0.49	0.49
4.2	0.19	0.18	0.18	0.18	0.18	0.18	**14.4**	0.52	0.51	0.51	0.50	0.50	0.50
4.4	0.19	0.19	0.19	0.19	0.19	0.18	**14.6**	0.53	0.52	0.51	0.51	0.51	0.50
4.6	0.20	0.20	0.19	0.19	0.19	0.19	**14.8**	0.54	0.53	0.52	0.52	0.51	0.51
4.8	0.21	0.20	0.20	0.20	0.20	0.20	**15**	0.54	0.53	0.53	0.52	0.52	0.52
5	0.21	0.21	0.21	0.20	0.20	0.20	**15.2**	0.55	0.54	0.53	0.53	0.53	0.52
5.2	0.22	0.21	0.21	0.21	0.21	0.21	**15.4**	0.56	0.55	0.54	0.54	0.53	0.53
5.4	0.23	0.22	0.22	0.22	0.22	0.21	**15.6**	0.56	0.55	0.55	0.54	0.54	0.53
5.6	0.23	0.23	0.23	0.22	0.22	0.22	**15.8**	0.57	0.56	0.55	0.55	0.54	0.54
5.8	0.24	0.23	0.23	0.23	0.23	0.23	**16**	0.58	0.56	0.56	0.55	0.55	0.55
6	0.25	0.24	0.24	0.24	0.23	0.23	**16.2**	0.58	0.57	0.57	0.56	0.56	0.55
6.2	0.25	0.25	0.24	0.24	0.24	0.24	**16.4**	0.59	0.58	0.57	0.57	0.56	0.56
6.4	0.26	0.25	0.25	0.25	0.25	0.25	**16.6**	0.60	0.58	0.58	0.57	0.57	0.57
6.6	0.27	0.26	0.26	0.26	0.25	0.25	**16.8**	0.60	0.59	0.59	0.58	0.58	0.57
6.8	0.27	0.27	0.26	0.26	0.26	0.26	**17**	0.61	0.60	0.59	0.59	0.58	0.58
7	0.28	0.27	0.27	0.27	0.27	0.26	**17.2**	0.62	0.60	0.60	0.59	0.59	0.58
7.2	0.29	0.28	0.28	0.27	0.27	0.27	**17.4**	0.62	0.61	0.60	0.60	0.59	0.59
7.4	0.29	0.29	0.28	0.28	0.28	0.28	**17.6**	0.63	0.62	0.61	0.61	0.60	0.60
7.6	0.30	0.29	0.29	0.29	0.29	0.28	**17.8**	0.64	0.62	0.62	0.61	0.61	0.60
7.8	0.31	0.30	0.30	0.29	0.29	0.29	**18**	0.64	0.63	0.62	0.62	0.61	0.61
8	0.31	0.31	0.30	0.30	0.30	0.30	**18.2**	0.65	0.64	0.63	0.62	0.62	0.62
8.2	0.32	0.31	0.31	0.31	0.30	0.30	**18.4**	0.65	0.64	0.64	0.63	0.63	0.62
8.4	0.33	0.32	0.32	0.31	0.31	0.31	**18.6**	0.66	0.65	0.64	0.64	0.63	0.63
8.6	0.33	0.33	0.32	0.32	0.32	0.31	**18.8**	0.67	0.65	0.65	0.64	0.64	0.63
8.8	0.34	0.33	0.33	0.33	0.32	0.32	**19**	0.67	0.66	0.66	0.65	0.64	0.64
9	0.35	0.34	0.34	0.33	0.33	0.33	**19.2**	0.68	0.67	0.66	0.66	0.65	0.65
9.2	0.35	0.34	0.34	0.34	0.34	0.33	**19.4**	0.69	0.67	0.67	0.66	0.66	0.65
9.4	0.36	0.35	0.35	0.35	0.34	0.34	**19.6**	0.69	0.68	0.67	0.67	0.66	0.66
9.6	0.37	0.36	0.35	0.35	0.35	0.35	**19.8**	0.70	0.69	0.68	0.67	0.67	0.66
9.8	0.37	0.36	0.36	0.36	0.36	0.35	**20**	0.71	0.69	0.69	0.68	0.68	0.67
10	0.38	0.37	0.37	0.36	0.36	0.36	**x**	**x**	**x**	**x**	**x**	**x**	**x**

Table B.2 Parameters for obtaining optimal orientation of PV panels

γ	β	f_s	γ	β	f_s
-15	0	0.12	5	0	0.12
-15	5	0.13	5	5	0.13
-15	10	0.13	5	10	0.13
-15	15	0.13	5	15	0.13
-15	20	0.13	5	20	0.13
-15	25	0.13	5	25	0.13
-15	30	0.13	5	30	0.13
-15	35	0.13	5	35	0.13
-15	40	0.13	5	40	0.13
-15	45	0.13	5	45	0.13
-15	50	0.12	5	50	0.12
-15	55	0.12	5	55	0.12
-15	60	0.11	5	60	0.11
-10	0	0.12	10	0	0.12
-10	5	0.13	10	5	0.13
-10	10	0.13	10	10	0.13
-10	15	0.13	10	15	0.13
-10	20	0.13	10	20	0.13
-10	25	0.13	10	25	0.13
-10	30	0.13	10	30	0.13
-10	35	0.13	10	35	0.13
-10	40	0.13	10	40	0.13
-10	45	0.13	10	45	0.13
-10	50	0.12	10	50	0.12
-10	55	0.12	10	55	0.12
-10	60	0.11	10	60	0.11
-5	0	0.12	15	0	0.12
-5	5	0.13	15	5	0.13
-5	10	0.13	15	10	0.13
-5	15	0.13	15	15	0.13
-5	20	0.13	15	20	0.13
-5	25	0.13	15	25	0.13
-5	30	0.13	15	30	0.13
-5	35	0.13	15	35	0.13
-5	40	0.13	15	40	0.13
-5	45	0.13	15	45	0.13
-5	50	0.12	15	50	0.12
-5	55	0.12	15	55	0.12
-5	60	0.11	15	60	0.11
0	0	0.12	x	x	x
0	5	0.13	x	x	x
0	10	0.13	x	x	x
0	15	0.13	x	x	x
0	20	0.13	x	x	x
0	25	0.13	x	x	x
0	30	0.13	x	x	x
0	35	0.13	x	x	x
0	40	0.13	x	x	x
0	45	0.13	x	x	x
0	50	0.12	x	x	x
0	55	0.12	x	x	x
0	60	0.11	x	x	x

Table B.3 Sensitivity analysis of NPV with respect to varying Size Factor and interest rate

NPV (Million USD)					
i (%) / S_F	**5**	**10**	**15**	**20**	**25**
1	2.36	1.35	0.78	0.43	0.19
1.5	3.48	1.99	1.14	0.62	0.27
2	4.39	2.48	1.40	0.73	0.29
2.5	5.07	2.82	1.54	0.75	0.22
3	5.07	2.82	1.54	0.75	0.22
3.5	5.82	3.08	1.51	0.55	-0.09
4	5.91	3.01	1.35	0.33	-0.34
4.5	5.83	2.83	1.11	0.05	-0.64
5	5.64	2.57	0.81	-0.27	-0.98