Techno-Economic Analysis of Integrating Renewable Electricity and Electricity Storage in a Typical Family House in the Turkish Republic of Northern Cyprus

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ABSTRACT

The world's energy consumption has increased due to the rapid increase in population. Many developing countries including the Turkish Republic of Northern Cyprus are relying on conventional energy resources to generate electricity. These sources add a great part of CO_2 emissions in the environment leading to global warming and climate change. Utilization of renewable energy sources e.g., solar, wind, etc. along with energy storage devices can reduce the usage of fossil fuels and it can also reduce the higher electricity bills. This study aims to integrate solar energy with a grid for a single-family house in Gönyeli, Northern Cyprus. The techno-economic analysis of the proposed system can determine the feasibility of a system in the selected location. It uses online available resources and HOMER Pro software to simulate four different configurations. The results show that the grid-connected solar system shows the lowest NPC of $15,327 and COE of $0.0365 than other configurations. However, due to the load shedding in the area, battery storage is crucial so that it can supply power during grid outages. The simulation was carried out for lead-acid and lithium-ion batteries. Results show that lead acid battery is cost-effective and provide the more optimal solution to meet the load demand with NPC of $24,547 and COE of $0.0563. Solar system integrated with lead acid battery is the most optimal system for a single-family house. The results from this research work can help effective power generation in the area and it also contributes to the research and development of renewable energy integration with energy storage in Northern Cyprus.

Keywords: Renewable Energy, Solar Home System, Techno-Economic Analysis, On-Grid, PV System, Energy Storage

ÖZ

Hızlı nüfus artışına bağlı olarak dünyanın enerji tüketimi artmıştır. Kuzey Kıbrıs Türk Cumhuriyeti de dahil olmak üzere birçok gelişmekte olan ülke, elektrik üretmek için konvansiyonel enerji kaynaklarına güvenmektedir. Bu kaynaklar, küresel ısınmaya ve iklim değişikliğine yol açan ortamdaki CO2 emisyonlarının ,lbüyük bir bölümünü oluşturmaktadır. Güneş, rüzgar vb. gibi yenilenebilir enerji kaynaklarının enerji depolama cihazlarıyla birlikte kullanılması, fosil yakıtların kullanımını azaltabilir ve aynı zamanda yüksek elektrik faturalarını da azaltabilir. Bu çalışma, Kuzey Kıbrıs Gönyeli'de tek ailelik bir ev için güneş enerjisini şebekeye entegre etmeyi amaçlamaktadır. Önerilen sistemin tekno-ekonomik analizi, bir sistemin seçilen yerdeki fizibilitesini belirleyebilir. Dört farklı konfigürasyonu simüle etmek için çevrimiçi mevcut kaynakları ve HOMER Pro yazılımını kullanır. Sonuçlar, şebekeye bağlı güneş sisteminin diğer konfigürasyonlara göre en düşük NPC'yi $15.327 ve COE'yi $0,0365 gösterdiğini gösteriyor. Ancak, bölgedeki yük atma nedeniyle, şebeke kesintileri sırasında güç sağlayabilmesi için pil depolaması çok önemlidir. Kurşun-asit ve lityum-iyon piller için simülasyon gerçekleştirilmiştir. Sonuçlar, kurşun asitli akünün uygun maliyetli olduğunu ve NPC $24,547 ve COE $0,0563 ile yük talebini karşılamak için daha uygun bir çözüm sağladığını göstermektedir. Kurşun asit batarya ile entegre güneş enerjisi sistemi, müstakil bir ev için en uygun sistemdir. Bu araştırma çalışmasının sonuçları, bölgede etkili enerji üretimine yardımcı olabilir ve ayrıca Kuzey Kıbrıs'ta enerji depolama ile yenilenebilir enerji entegrasyonunun araştırılmasına ve geliştirilmesine katkıda bulunur.

Anahtar Kelimeler: Yenilenebilir Enerji, Solar Ev Sistemi, Tekno-Ekonomik Analiz, On-Grid

To my Family, Teachers, and Friends……

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BESS	Battery Energy Storage Systems
COE	Cost of energy
CSP	Concentrated Solar Panel
EAC	Electricity Authority of Cyprus
ESS	Energy Storage Systems
GHG	Greenhouse Gases
HOMER	Hybrid Optimization of Multiple Energy Resources
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KIB-TEK	KIBRIS TÜRK ELEKTRİK KURUMU
LCOE	Levelized cost of electricity
MCA	Multi – Criteria Analysis
NPC	Net Present Cost
PV	Photovoltaic
RES	Renewable Energy Sources
S-CHP	Solar based Combined Heat and Power systems
TRNC	Turkish Republic of Northern Cyprus

Chapter 1

INTRODUCTION

1.1 Background

The world is dealing with big challenges like climate change, natural resource depletion and water scarcity. Climate variability is caused by the greenhouse gas (GHG) emissions from the use of conventional energy sources (aka. fossil fuels) such as coal, oil and natural gas for electricity generation, transportation, and industrial sector. Utilizing natural energy sources for the electricity generation can reduce the GHG emissions. Greenhouse gases include carbon dioxide (CO_2), Nitrous oxide (N_2O), Methane (CH_4), Hydrochloro-fluorocarbons (HCFCs), Hydrofluorocarbons (HFCs) and Ozone (O_3) [1]. The global energy consumption has been increased drastically due to various factors such as population growth, industrialization, urbanization, and economic development. As people are moving into the cities and adopting modern lifestyle, their demand for energy intensive services like heating, cooling, transportation, lighting, and other modern equipment also increased. Around 90% of people life is spent within the buildings, which makes it a big consumer of electricity [2]. According to IEA report, in 2021 30% global energy consumption and 27% GHG emission from energy sector were the result of buildings operation [3]. Therefore, it is crucial to take energy efficient and environment friendly measures within next decade. In many countries, main sources of electricity generation are thermal power plants and thus energy sector is focused majorly on oil, natural gas, coal, etc [4].

1.2 Renewable Energy Resources

Renewable energy resources such as solar, wind, hydropower, biomass, tidal waves and geothermal are unlimited natural resources which can be used for clean electricity generation. These natural resources are being utilized globally for cheaper electricity generation in residential, commercial, and industrial sectors. Natural resources main advantage over fossil fuels is that it does not emit harmful greenhouse gases e.g., carbon dioxide, nitrous oxide and other gases which pollute the environment and exacerbate the phenomenon of global warming [5]. They reduce dependence on fossil fuels for electricity generation and also, diversify the energy supply system. Renewable energy sources can also be used for fuel production for mass transportation and industrial use. Every country has its own renewable resource which can only be used in that country. They contribute a lot in the country's economic growth and its development along with academia, research and development.

1. **Solar Energy**

Solar energy is a reliable and unlimited natural resource. Solar panels take energy from sun and convert it into electricity with the help of a converter. This electricity can be used to power a house, shop, factory, industry. This technology is widely used in the world because of their ability to reduce GHG emissions at a large scale. Solar energy is a cheapest natural resource that an average house owner can easily afford it. In Northern Cyprus, abundant solar resource is available [6].

Figure 1: Solar Panels

2. **Wind energy**

Wind energy uses wind to generate electricity with the help of large wind turbines. These turbines convert rotational energy of wind fans into the kinetic energy by the impact of wind, with which we get the electric power. Wind turbine are installed at large area because they are big and heavy. They are installed at a large scale. Cyprus is a Mediterranean island, it has a great potential of wind [7].

Figure 2: Wind Turbines

3. Biomass Energy

This energy is made from the solid fuels obtained from plants and then, conversion into electricity. It includes organic materials to generate electricity. This renewable resource technology is clean and energy efficient. Electricity is generated from plants, wood, crops, animal manure, industrial and domestic waste, etc. by converting them into liquid, solid and gaseous fuels [8].

Figure 3: Biomass Energy

4. Geothermal Energy

Geothermal energy is obtained by using the heat within the earth's crust. It is a renewable energy resource because heat is continuously produced in the earth's crust and is always available [9]. This heat energy is used for many industrial, commercial, agricultural and residential applications such as water heating, space heating, bathing and different industrial processes.

Figure 4: Geothermal Energy

1.3 Topic Motivation

Global warming is a serious global issue that has attained world's attention in recent years. The special report published by Intergovernmental Panel on Climate Change (IPCC) on global warming and climate change in October 2018 explains mitigation and adaptation measures in order to keep the global warming temperature to 1.5 ^{0}C [10]. This goal requires collaboration from the whole world on a global level and each country is already on this road. European countries have a great potential of renewable energy and they are becoming a leader in its deployment. According to Eurostat statistics, solar, wind and other green energy sources in Europe contributed around 21.8% to its total energy consumption [11]. Northern Cyprus has an abundance of solar and wind energy because it is a Mediterranean island near Turkey. This island is fully dependent on imported energy because it lacks any natural gas or petroleum oil deposits. By including renewable energy sources into their energy mix, they hope to lessen their reliance on imported oil [12]. Therefore, there is greater demand for clean and green electricity that is more sustainable and economically feasible. In residential areas, there has been a notable rise in the installation of Photovoltaic (PV) systems on rooftops. The growing popularity of PV systems has transformed residential rooftops into a thriving hub for solar energy generation.

1.4 Problem Statement

Recent policy developments indicate an emerging trend of increasing tariffs for electricity usage and a diminishing opportunity for households to sell their surplus electricity back to the grid. These policy changes have significant implications for households seeking to optimize the financial benefits of their photovoltaic (PV) systems. As a result, there is a growing interest among households in maximizing self-consumption of PV-generated electricity as a means to minimize the costs associated with relying on grid electricity. One effective strategy to enhance self-consumption is the adoption of Energy Storage Systems (ESS) as a complementary solution. These systems enable the temporary storage of surplus energy generated by PV systems in a Household Energy Storage (HES) unit, which can then be utilized to meet residential energy demands during periods of low PV production. By effectively managing and utilizing stored energy, households can reduce their reliance on grid electricity and minimize expenses. However, it is essential to consider the costs associated with implementing ESS for residential purposes. The financial viability of investing in batteries for self-consumption improvement has raised concerns among homeowners. The current economic landscape may pose challenges in recovering the initial investment costs of residential batteries, particularly when compared to the potential profitability of selling excess energy back to the grid. Therefore, it becomes crucial to carefully evaluate the economic feasibility of residential battery exploitation in light of these considerations. By thoroughly assessing factors such as battery cost, potential savings from reduced grid consumption, and potential earnings from selling excess energy, homeowners can make informed decisions regarding the adoption and utilization of ESS.

To address these concerns, further research is necessary to explore and analyze the current and projected costs of ESS, considering factors such as battery lifespan, efficiency, maintenance, and potential technological advancements. Additionally, an examination of electricity pricing structures, regulatory frameworks, and market dynamics is vital to provide comprehensive insights into the financial implications of self-consumption strategies and the potential profitability of selling energy back to the grid.

1.5 Aim of the Study

The study aims to perform the technical and economic analysis of integrating renewable electricity and electricity storage systems in a "typical" family house that consists of four people two adults and two children in Turkish Republic of Northern Cyprus (TRNC). This techno-economic analysis will determine the most feasible case of the system with respect to the total net present cost (NPC) of the system.

The aim of this study will be achieved by completing following objectives**:**

1. Examine the energy sector of the case study location especially its residential sector.
2. Design and develop a technical and economic model in HOMER Pro software to analyze the feasibility of domestic rooftop solar PV systems.
3. Compare the off grid solar PV system with grid connected PV system for a typical house in Cyprus.

1.6 Assumptions

This study is conducted for a typical family of four people in Gönyeli, northern Cyprus. Hypothetical electrical load consumption for the house is assumed. Electrical equipment such as Television, fridge, air conditioner, LED bulbs, fans, washing machine, charging points etc. are almost same in each and every averages house.

1.7 Significance of the Research

This research work possess a special significance in the research and development of this field. The techno-economic analysis of solar PV system for a typical house in Gönyeli will determine the feasibility of renewable energy system. It will also compare the overall net present cost of the system by comparing different scenarios cost with the base case. This study findings will help researchers in academia to improve the renewable energy systems and optimize it to lowest possible cost with highest energy efficiency.

1.8 Summary

In this chapter, thesis objectives are presented with basic introduction of renewable energy resources solar, wind, biomass, geothermal. It also explains the research motivation, aim of the study, research problem and significance of this research.

1.9 Thesis Structure

Chapter 1 has discussed the basics of the thesis with problem statement and thesis objectives.

Chapter 2 presents detailed literature review on renewable energy development in Northern Cyprus.

Chapter 3 explained the methodology of the research.

Chapter 4 discusses and analyze the results and explains the research findings.

Chapter 5 concludes the thesis findings.

Chapter 2

LITERATURE REVIEW

2.1 Energy Sector of Northern Cyprus

Turkish Republic of Northern Cyprus (TRNC) is strategically located between Europe and Middle East which makes it a valuable source of energy harvesting. Northern Cyprus has a great renewable energy resource potential available for the energy production. Cyprus is the third island of its kind in the Mediterranean Sea in terms of its area and geographical location, and still rely on traditional energy sources including coal, natural gas, and petroleum oil [13].

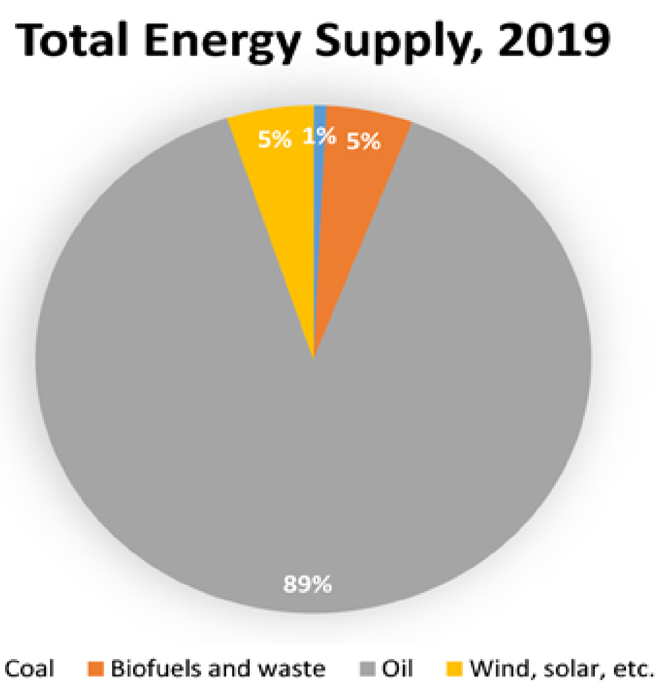

Figure 5: Total Energy Supply For Cyprus (IEA 2021b)

TRNC energy mix is dominated by oil with 85% share and has very less share of renewable energy. Larnaca oil refinery was closed in 2004 due to which this refinery became the oil products import and storage center. Cyprus import oil from Israel that holds almost one third of its total oil imports, followed by other countries that are Greece (27%) and Netherland (13%) [14]. According to global petrol prices, average price of gasoline in Nicosia was 1.41 Euro on 10th of April 2023 [15]. And electricity price since September 2022 is 0.382 USD/KWh for households and 0.393 USD/KWh for businesses commercial and industrial [16]. Cyprus government's priority is to reduce oil dependence.

The electricity authority of Cyprus (EAC) is a national owned by the state of TRNC is a big player of power generation, transmission and distribution which is accountable for 3/4th of the total electricity [17]. KIB-TEK, the Cyprus Turkish Electricity Authority, operates as an electricity generation and distribution company serving the Northern part of Cyprus Island. KIB-TEK employs a power generation infrastructure that includes six 17.5 MW diesel generators and two 60 MW steam power plant generators, effectively meeting both base load and peak load electricity demands [18].

There is another energy generation company that sell electricity to the main grid. This company is known as AKSA Energy which is an independent power producer in Turkey and Northern Cyprus and has 16 power plants with its installed capacity of 2,198 MW. Power generation is a big contributor in greenhouse gas emissions in Cyprus [19].

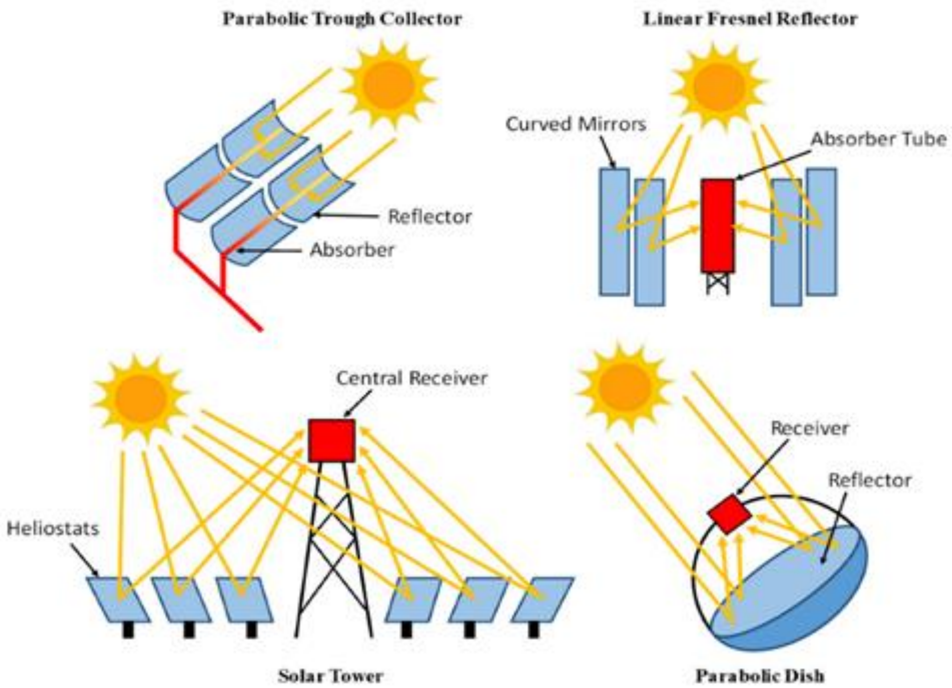

Figure 6: Concentrated Solar Power Technologies

2.2 Solar Energy

Sun energy is a renewable and sustainable source of energy that has received a lot of attention recently because of its potential to solve the world's energy crisis and reduce carbon emissions. Solar energy is derived from the sun's rays and can be used in a variety of ways, including photovoltaic (PV) and concentrated solar power (CSP) systems [20]. PV systems simply convert sunlight into electricity, but CSP systems focus the sun's energy into a small area, which then warms a fluid to generate power. Both technologies have made tremendous strides in efficiency and cost reduction, putting them on par with traditional fossil fuels. The figure 6 above shows different concentrated solar energy technologies that are used to convert solar energy to electricity in an efficient and clean manner [21].

Advantages and Disadvantages

Solar photovoltaic energy is a rapidly growing renewable energy resource all over the world. Solar energy has a great use in all sectors such as residential, commercial and industrial. Solar energy has various applications such as water heating, space heating, water pumping, street lightning, building integrated PV systems and as an electricity backup source. It has various advantages, including reduced greenhouse gas emissions, decreased energy prices, clean energy source, reliable system, increased energy security, cost effective, high availability, low maintenance, job creation, noiseless system and environment friendly [22]. With advantages, PV systems also incorporate some limitations such as it requires high initial investment to install a PV system solar farms require large area whether on rooftop or on ground, and requires a geographical location that can provide maximum solar irradiation [23].

This thesis aims to investigate solar energy potential in TRNC as a viable origin of energy and its impact on the environment and economy. The research will analyze the state of the art solar energy high tech, its strengths and limitations, and its future prospects for deployment in residential sector. Overall, this thesis will provide a comprehensive understanding of the potential of solar energy as a sustainable and renewable source of energy, and its role in meeting the electricity demand of a house and addressing global energy challenges.

Factors affecting solar energy potential:

Several factors can influence the potential of solar energy, including:

1. **Location and Climate:** The amount of solar radiation received at a specific site is determined by its latitude, altitude, and meteorological conditions. Solar

radiation is more intense near the equator than farther away. Furthermore, places with higher elevations and clear sky receive more sunshine than those with lower elevations and cloudy skies [24].

2. **Angle of Incidence:** The angle at which sunlight strikes a solar panel impacts the amount of energy that may be produced. Solar panels should ideally be installed perpendicular to the sun's rays. Panels positioned at an insufficiently steep or shallow angle may not get enough sunlight [25].
3. **Shading:** When solar panels are partially shadowed by trees, buildings, or other objects, their energy output is reduced. As a result, it is critical to place solar panels in areas with little shade [26].
4. **Panel Efficiency:** The ability of a solar panel to convert sunlight into useable electricity is referred to as its efficiency. High-efficiency panels cost more but produce more electricity per unit area [27].
5. **System Design and Installation:** A solar energy system's design and installation can have a substantial impact on its energy production. Proper installation, including panel and wiring arrangement, may assure optimal efficiency and reduce energy losses [28].
6. **Regular maintenance:** such as cleaning the panels and inspecting for damage, can help to guarantee that a solar energy system performs at peak efficiency [29].
7. **Time of day and Season:** The amount of solar radiation received varies based on the time of day and the season. When the sun is at its highest point in the sky, which is usually around noon, solar panels produce the greatest energy. Furthermore, due to fewer daylight hours and lower solar radiation levels, solar energy generation is often lower during the winter months [30].

Types of solar cells

Solar cells convert solar energy into electricity with the help of photoelectric effect. The photoelectric effect is a phenomenon that occurs when a substance is exposed to light (typically in the form of photons) of a specific frequency or higher. Heinrich Hertz discovered this effect in 1887, and Albert Einstein characterized it as a fundamental element of quantum mechanics in 1905 [31].

The photovoltaic effect occurs when two photons are absorbed simultaneously in a process called two-photon photovoltaic effect. This can increase the efficiency of solar cells by using higher-energy photons that would otherwise be wasted. The photovoltaic effect can be used to produce electricity from sunlight or other light sources using solar cells or photovoltaic cells. These are devices that convert light energy directly into electrical energy by the photovoltaic effect. They are made of semiconducting materials that have a p-n junction, which creates an electric field that separates the charge carriers when they are excited by light. The electric current can then be extracted to an external circuit [32]. Figure 7 shows a photovoltaic cell.

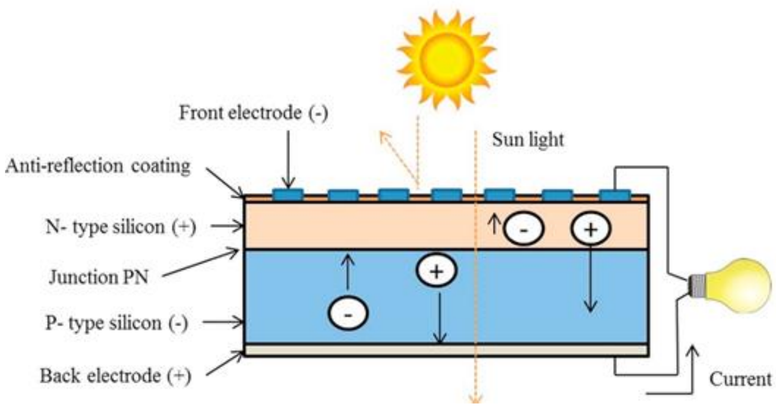

Figure 7: Photovoltaic Cell

Figure 8 presents different types of solar cells that are used to generate electric power and also in research and development area.

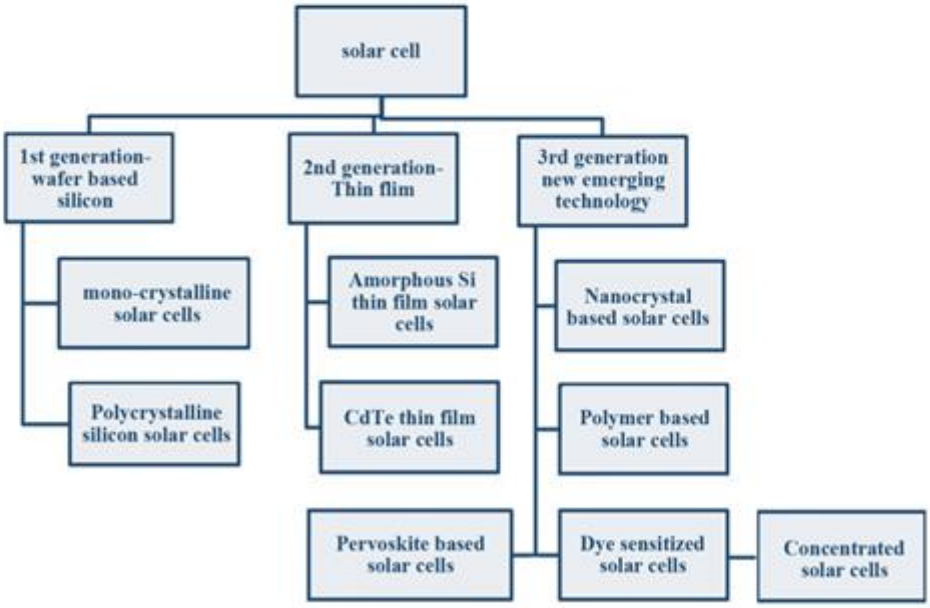

Figure 8: Different Types Of Solar Cells

1. **Crystalline silicon solar cells**

   Crystalline silicon solar cells are the most widely used 1st generation wafer-based silicon solar cells in the world. These are made of silicon wafers and can be either monocrystalline or polycrystalline.

   Monocrystalline (mono c-Si) cells are more efficient with efficiency range 17-18%, but also more expensive. Polycrystalline (poly c-Si) cells are less efficient but are cheaper to produce. They have an efficiency range of 12-14% and are durable, making them a popular choice for residential and commercial applications [33]. Figure 9 differentiates the mono c-Si and poly c-Si.

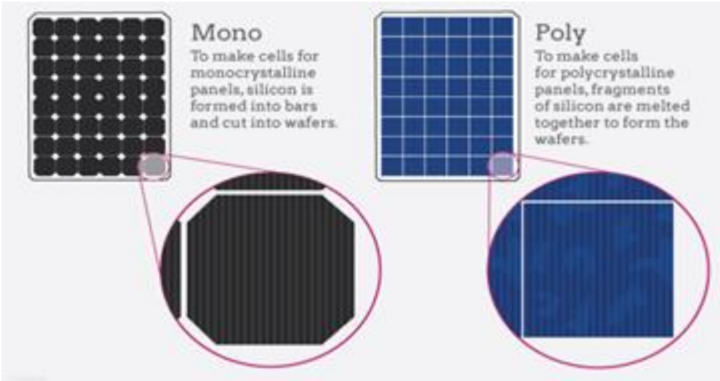

Figure 9: Mono c-Si and Poly c-Si

2. Thin-film solar cells

Figure 10 illustrates the production process of second-generation thin-film solar cells, which involve depositing a thin layer of photovoltaic material onto a substrate. These cells offer cost advantages compared to crystalline silicon cells and can be fabricated using various materials such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si). Although thin-film cells have lower efficiency levels, typically ranging from 5% to 13% [34], they possess the advantage of flexibility and can be utilized in a broader array of applications, including building-integrated photovoltaics (BIPV) and portable electronic devices.

Figure 10: Thin Film Solar Cell

3. **Polymer solar cells**

The third generation which is emerging new technology consists of polymer solar cells also known as organic solar cells, are made of organic materials, such as polymers and small molecules shown in figure 11. They are lightweight, flexible, and can be made using low-cost printing techniques. Organic cells are less efficient than crystalline silicon cells and thin-film cells, with an efficiency range of 3-10% [35]. However, they have the potential to be used in a wider range of applications, such as wearable electronics and foldable solar panels.

Figure 11: Polymer Solar Cells

4. **Perovskite solar cells**

Perovskite solar cells are a new type of solar cell that has gained significant attention in recent years. They are made of perovskite materials, such as methyl ammonium lead iodide (MAPbI3), and have achieved high efficiencies of over 25%, figure 12. Perovskite cells are still in the research and development phase and are not yet widely available. However, they have the potential to be a game-changer in the solar industry due to their high efficiency and low cost [36].

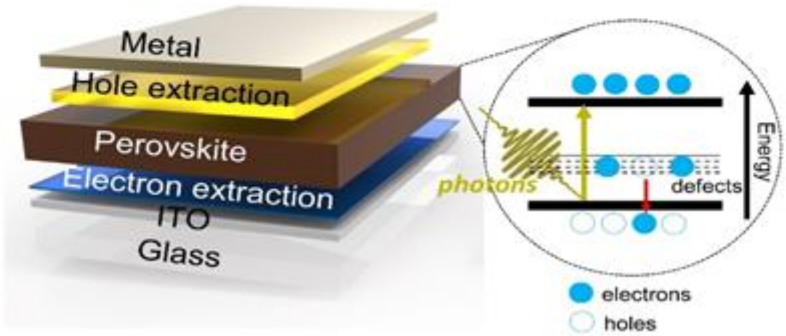

Figure 12: Perovskite Solar Cell

2.3 Literature Review

There are some previous studies which shows the development of renewable energy resources (RES) in TRNC. Tsilingiridis et al examined the options to exploit the renewable energy sources in Northern Cyprus to reduce the greenhouse gas emissions from power sector. The study explained that the power sector is the major contributor of total GHG emissions in Cyprus and found that electricity production with RES can reduce GHG at large extent [37]. Solyali et al. (2010) identified and determined the economically feasible renewable energy sources for Northern Cyprus. The paper provides an insight into solar and wind energy sources that are available in abundance due to its amazing geographical location [38]. Makrides et al. (2010) investigated the solar energy potential in Cyprus and also discussed different solar energy technologies [39]. Solyali et al. (2012) first time analyzed the usage of solar energy for domestic purpose and examined its financial implications [40].

Renewable energy resources such as solar and wind potential has been assessed by Yenen et al. (2013). The advantages and disadvantage of hybrid system (wind and solar) in order to create energy generation portfolio was discussed [41]. Cyprus has highest solar energy potential in Europe. Sabah et al. (2015) assessed the total electricity production from Solar farm at two different locations in Cyprus [42]. A guide to install the solar photovoltaic at a large scale was presented by Şenol et al. (2016). The simulation was accomplished using PV*SOL for different capacities [43]. A study by Lopez-Lorente et al. (2023) presented the effect of soiling on photovoltaic systems. It also explained other factors affecting the performance of solar PV panels. It has performed an experiment at the outdoor test facility of university of Cyprus in Nicosia. The authors also compared different soiling models based on Machine Learning (ML) with the physical Model. And the results showed that physical Model performance was better than ML models [44].

KIB-TEK is the first solar power plant that is with grid connected with a capacity of 1.275 MW and is located in Serhatkoy. This study investigated different potential factors that can affect the plant performance such as total investment, plant efficiency, performance ratio and capacity factor. Simulation is performed in PVsyst software to determine the Viability for the construction of solar plants Similar to KIB-TEK [45]. As Cyprus is not a member of European electricity network, it is totally dependent on local power production. Having an independent power network Cyprus is facing high Electricity prices. To meet the Europe's target of 40% renewable energy in the total energy mix, Cyprus needs to fully utilize its renewable energy potential. In this study renewable energy integration into thermal plant with grid is simulated in an ENERGYPLAN simulation environment. Eight scenarios were modelled with different RES and study found that photovoltaic systems case scenario is the most feasible option [46].

A study by Temiz et al. (2022) has investigated, designed and analyzed the integration of solar energy thermodynamically using 1st and 2nd law approaches. The system was designed to meet the energy demand in a sustainable and efficient manner [47]. Yue wang et al. (2020) Evaluated the PV system on rooftop to determine its financial feasibility, investment attractiveness. The UK case study was also evaluated to check the impact of energy storage system ESS and use of electric vehicle EV as energy storage system [48]. María Herrando et al. (2018) modelled and optimize the techno economic performance of solar based combined heat and power systems (S-CHP) for three different locations: Athens (Greece), London (UK) and Zaragoza (Spain). The investigation was carried out for single family home applications such as domestic water heating, space heating and electric power for home. The results showed that optimized system can cover around 65% of the household electricity consumption in the specified locations [49]. Baran Yildiz et al. (2021) presents a comprehensive analysis of solar water heating system for 410 households in Australia. The study analyzed the potential of using and storing excess solar energy storage using the actual data with the help of thermal energy modelling software TRNSYS. The results showed that excess energy from solar system of 4.5kw can provide 48% of energy for daily water hating of an average house [50].

Simon Meunier et al. (2020) performed a sensitivity analysis on solar water pumping systems for residential households in rural areas. The study showed that six parameters of cost and performance are most important in the techno-economic optimal sizing of the solar PV water pumping system. These parameters are the solar PV module's peak power, the water tank volume, the cost of the water tank, the motor pump efficiency, the cost of the motor pump, and the lifetime of the PV water pumping system [51]. Davide Fioriti et al. (2022) proposed a multi-year methodology for the optimization of residential battery storage systems. The simulation of the complete battery lifetime was performed on a 15-minute time resolution till the battery degradation for load profiles in Italy. The economic analysis showed that average price of battery storage is around 400 euro per kwh while Net Present Value (NPV) and Payback period can reach 500-1500 euro and 8-11 years [52]. Noman Shabbir et al. (2022) discussed the solar photovoltaic system installation along with the optimal battery energy storage system (BESS). The study developed an efficient energy model to optimize the BESS and to reduce the total energy consumption cost and dependence on the grid. The study also conducted a detailed techno-economic analysis of the proposed system for three residential buildings with different electricity prices [53].

Serdar Açıkyıldız et al. (2022) examined the hybrid solar energy system by analyzing the energy production and consumption data of Serhatköy region to find a more sustainable energy solution for TRNC electricity demand. The HOMER Pro simulation results show that the proposed hybrid system is cost-effective and can meet the technical requirements [54]. Nasser Alqahtani et al. (2021) developed a techno-economic model of a hybrid PV energy system that consists of rooftop solar panels with battery storage in HOMER Pro. The proposed system was designed to reduce the reliance on the electric grid and optimize the PV system in Neom City, Kingdom of Saudi Arabia (KSA). The study determined the NPV, Levelized cost of energy (LCOE), PV panel's optimal orientation, tracking, optimal PV and battery size [55].

Apart from battery energy storage, there are other energy storage technologies, that different researchers have used in their research studies. Hoda Akbari et al. (2019) comprehensively explained the storage technologies in their research paper [56]. Alayat et al. (2018) determined wind energy potential in eight different locations in Northern Cyprus [57].

2.4 Summary

This chapter explained Northern Cyprus energy sector and energy mix and solar energy with different types of solar cells. The literature review presented shows that on global level there is so much research work on solar energy and its applications in different sectors. However, in Northern Cyprus very few studies were found which elaborate the solar energy potential in Northern Cyprus. Therefore, this study will work on the potential of solar energy and how it can lessen the use of fossil fuels and overcome high electricity prices in the region.

Chapter 3

RESEARCH METHODOLOGY

3.1 Single Family House – A Case Study

In this study, a typical single-family house is considered that is consists of four people where two are adults and other two are children. This family house electric load is currently being met by the purchased electricity from electric grid. The grid electricity is basically produced from fossil fuels and is costly. A solar panel system will be installed in this house in order to move to the cost effective, clean and green energy sources. Solar panels require large area, so these will be mounted on house rooftop. Figure 13 shows the off-grid solar home system that is dependent only on solar energy and battery. An off-grid solar home system consists of Solar PV modules, inverter, battery storage and household appliances. If the system is connected to the grid, then it will be a grid tied or on-grid system.

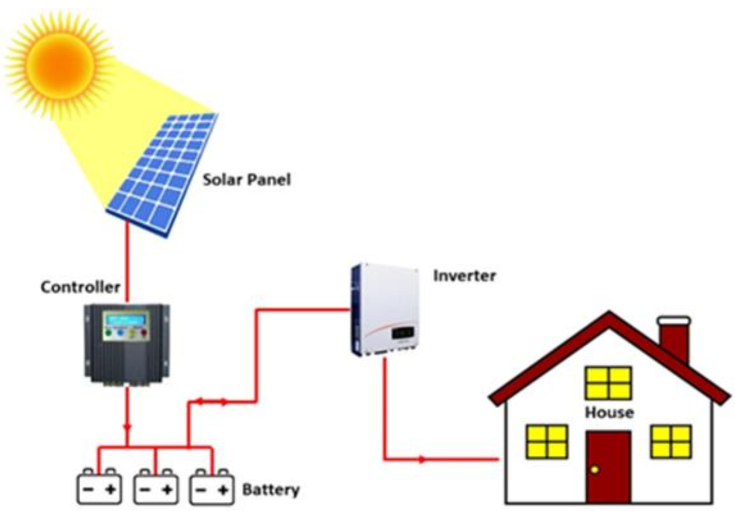

Figure 13: Solar home system

3.2 Research Methodology

In this research work, four different configurations will be evaluated using HOMER Pro software. The simulation is conducted for a household load in Gönyeli. Different technical and economical parameters are calculated using mathematical equations. A base case system will be served as a benchmark for the comparison against three different configurations of solar system on the basis of technical and economical parameters.

The evaluation of these parameters will aid in identifying the most viable system solution for the household, facilitated by the utilization of HOMER Pro software. The research will encompass an analysis of system economics, case scenarios, as well as detailed descriptions of the system components and their respective properties.

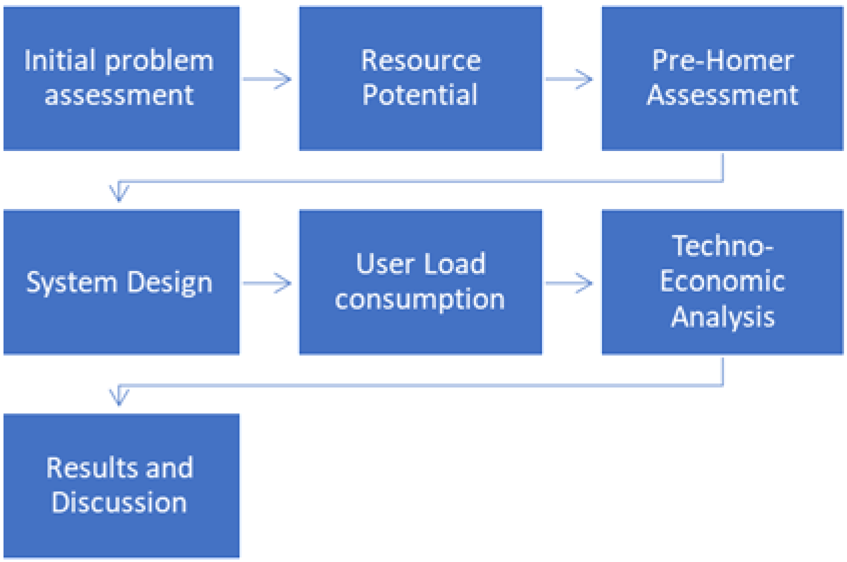

Figure 14: Methodology Flow Chart

Economics of the system

Table 1: System Economics

Constraints	Values
Nominal Discount Rate	8%
Real Discount Rate	5.88%
Expected inflation rate	2%
Project Lifetime	25 years
Annual capacity shortage	0.01%

3.3 System Configurations

1. **Only Grid – Base case**

This is the base case in which the total house load is being met by the electricity purchased from the main grid at the rate of ~ $0.16/kWh. A schematic diagram is shown in figure 15.

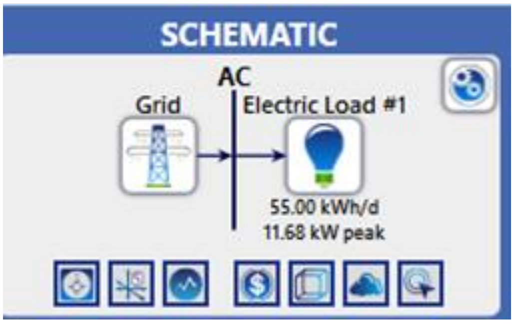

Figure 15: Grid Only- Base Case

2. **Grid And Solar PV System – Case 2**

   In this case, there is only renewable energy source (Solar PV) which is connected to grid to meet the house load demand. The schematic diagram for the model is shown in figure 16.

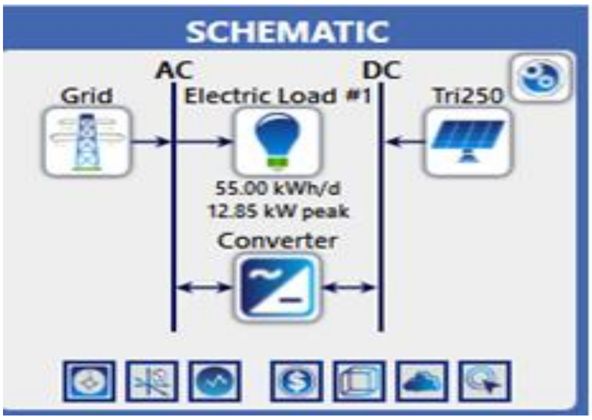

Figure 16: Grid Connected Solar System

I have chosen Trina Solar because of its efficiency and its economic viability. The selected solar panel is Trina Solar250TSM-250PA05.18. The solar resource has been downloaded for the selected location from the NASA Prediction of Worldwide Energy Resource (POWER) Database.

3. **Grid Connected Battery System - Case 3**

In this case, Lead acid battery storage and grid are present to serve the load demand. Electricity purchased from grid is stored in lead acid battery. The following figure shows schematic diagram of the proposed system.

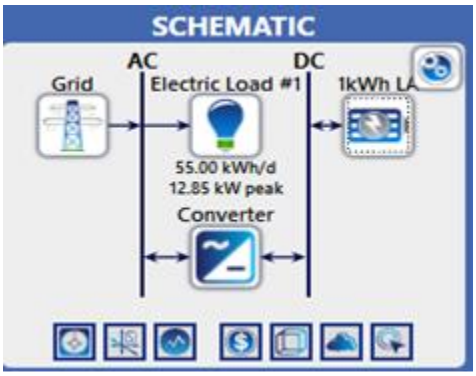

Figure 17: System With LA Battery

When there is load shedding in the town, the battery will provide a backup supply to the household. Grid outage has been introduced during the winter season from Nov to Feb at 19:00 hours daily for one hour as per geographical location shown in Figure 18.

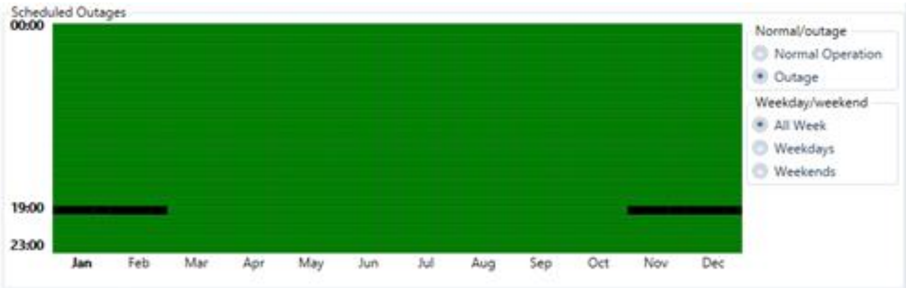

Figure 18: Grid Outage In Gönyeli

4. **Grid, PV, Battery System – Hybrid Case**

   This case consists of Trina solar panels, a Lead acid battery and a main grid. In this case solar and battery storage both will supply power to the house. The excess power generated from solar is sold back to the grid. This process is known as Net Metering. It is a billing mechanism where solar power system owners are credited for the electricity they sell to the grid. The sell back rate \$0.05/kWh is used in this study. The grid outage is same as it is in previous case. A Schematic diagram of hybrid system is shown below.

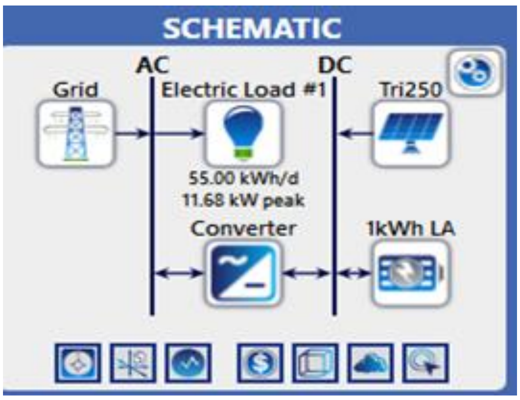

Figure 19: Hybrid Solar System

3.4 Site Selection

In this research work, residential load is calculated for a single family house in Gönyeli, Northern Cyprus. Gönyeli is a municipality located in Northern Cyprus. It is a suburb of the capital city of Nicosia also known as Lefkoşa, and it is situated on the northern outskirts of the city. Northern Cyprus is a Mediterranean island which covers the total area of 3,242 square kilometers. Its total population is around 300,000 as of 2021 [58]. Figures 20 and 21 shows the specific location area that is under consideration and map of the island.

Figure 20: Gönyeli House Building

Figure 21: Turkish Republic Of Northern Cyprus Map

Table 2: Selected site information

Location	Gönyeli Lefkoşa
Latitude (ºN)	35°12'42.8"
Longitude (ºE)	33°18'36.0"
Elevation (m)	220

Feed-in Tariff (FIT)

A feed-in tariff is a policy mechanism of an electric power company that provide financial incentives to individuals, business owners and organization for generating green and clean electricity using renewable energy resources e.g. solar, wind or biomass, by selling excess electricity to the main grid. FIT is a fixed rate that utilities pay to renewable energy generators for each kilowatt hour of electricity fed back to the grid. Feed-in tariffs for the residential electricity supply from KIB-TEK electric power company are given in the following table [59].

Table 3: Tariff Fees Effective as of July 2022 (KIB-TEK)

Residential Tariff	Value (TL)	Value (USD)	
1kwh energy price	3.3285	0.17	1 Turkish lira = 0.051 United States Dollar *(as 14th May, 2023)*
Fuel Cost	2.5711	0.13	
New Fixed price	0.7574	0.039	

3.5 House Load Consumption

A typical family house with 2800 sq. ft. approximate area has 4 people with 2 adults and 2 children. The house consists of four Bedrooms with four attached Restroom, Corridors, Lounge, Kitchen, laundry, courtyard and garage. The household appliances of a typical house are refrigerator, TV, laptop, washing machine, electric heater, air conditioner, fan, microwave oven.

Table 4 presents the electrical load consumption of a hypothetical single family house. The average daily energy consumption is 42.260 kWh/day. There is high electricity consumption during summers due to increased use of air conditioners, refrigerators, fans etc.

Table 4: Electric Load Consumption

Appliances	Quantity	Watts/hour	Total Watts	Hours/day	Energy (kWh/day)
Tube lights	5	40	200	5	1000
Bulbs	20	18	360	6	2160
Fans	5	100	500	15	7500
Refrigerator	1	150	150	24	3600
Air conditioner	3	1500	4500	5	22500
Washing machine	1	1200	1200	1	1200
Clothes dryer	1	1500	1500	0.5	750
Iron	1	1000	1000	0.5	500

Microwave oven	1	700	700	0.5	350
Laptop / mobile	6	100	600	4	2400
TV/LED	1	100	100	2	200
Other	1	100	100	1	100
Total			**10910**	**42260**	
Total Avg. daily consumption			**42.260 kWh/day**		

System Losses:

To accurately calculate daily load consumption, it is important to consider any system losses or inefficiencies that can affect the total amount of energy consumed. These losses could be losses due to transmission and distribution of electricity, losses due to electrical resistance, losses due to heat and other factors. This energy typically amounts to around 30% of the total energy consumption, although the exact amount may vary depending on the specific circumstances [60].

Including 30% system losses the average daily energy consumption becomes:

$$= 42.260 \times 1.3 = 54.938\ kWh/day = 55\ kWh/day$$

Therefore, monthly energy consumption will be

$$Avg. Monthly = 55 \times 30 = 1650\ kWh/month$$

$$Avg.\ Annual = 1650 \times 12 = 20{,}075\ kWh/year$$

Figure 22 shows daily electrical load profile of the house in graphical form.

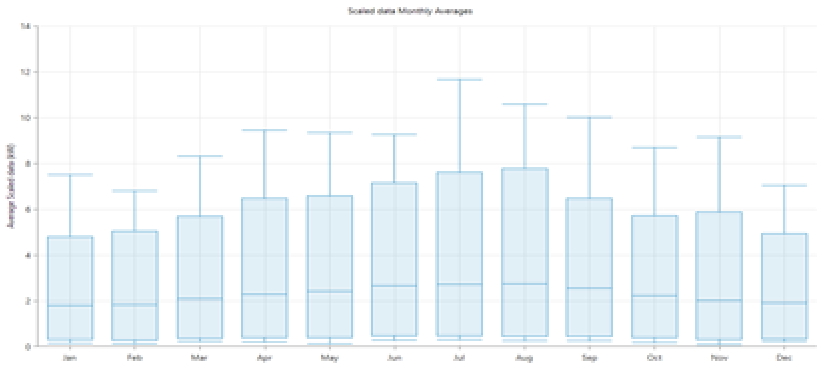

Figure 22: Seasonal Load Profile

3.6 Components

The proposed system components are described below. Their cost parameters are presented in Appendix.

3.6.1 Photovoltaic Solar Panels

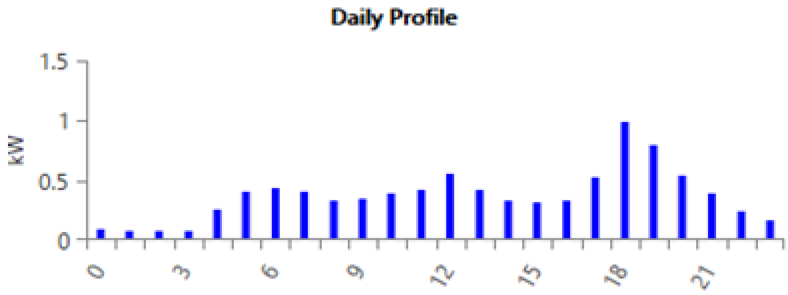

Figure 23: Daily Load Profile

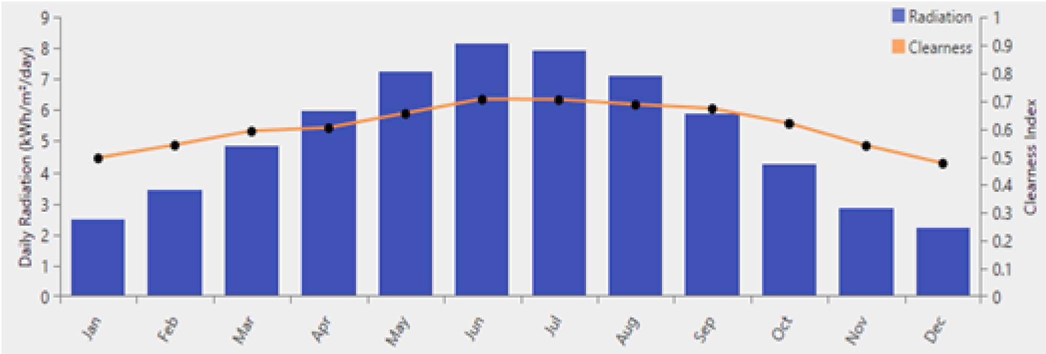

Figure 24: Solar GHI Resource of TRNC

Crystalline Solar panels are widely used in the residential and commercial sectors. In this study, Flat plate Multi c-Si Trina solar modules are used. Solar panel's global horizontal irradiance (GHI) resource is downloaded from the NASA Prediction of Worldwide Energy Resource (POWER) database shown in the figures above. On average, the estimated annual global solar radiation of Northern Cyprus ranges between 2000 kWh/m^2 and 1800 kWh/m^2 [61].

PV Module sizing:

$$Total\ Watt\ peak\ rating = \frac{Total\ watt\ hours\ required\ per\ day}{panel\ generation\ factor}$$

$$Total\ Watt\ peak\ rating = \frac{55kWh}{3.43} = 16.0349kw$$

$$Number\ of\ PV\ panels\ Required = 16034.9/250 = 64\ modules\ required$$

So , the system should be powered by at least 64 modules of 250Wp PV module to overcome the required energy.

The flat plate PV module (Trina Solar250TSM-250PA05.18) specifications are presented in the following table.

Table 5: Trina Solar250TSM-250PA05.18 Characteristics

Electrical characteristics at (STC)	**Value**
Maximum Power	250 W
Maximum Voltage	37.60 V
Maximum Current	8.55 A
Module Efficiency	13%
Operating temperature	44.1℃
Derating Factor	85%

3.6.2 Inverter

An inverter is a device that converts the DC electricity from solar panels into AC electricity that is used to run ac appliances in the house or it can be sold to the grid. In this system a general converter is used which electrical characteristics are given below:

Table 6: DC-AC Solar Inverter

Electrical characteristics at (STC)	**Value**
Relative capacity	100%
Efficiency	95%
Lifetime	15 years

Inverter sizing:

$$Total\ Wattage\ of\ all\ household\ appliances\ =\ 10{,}910\ W$$

For safety purpose of the system, the inverter should be considered 25-30% bigger size.

$$Inverter\ size =\ 10{,}910\ W \times 1.30 = 14183\ W$$

The inverter size should be about 14KW or greater.

3.6.3 Battery Storage

1. **Lead Acid Battery**

A lead acid battery is a form of rechargeable battery that stores and releases electrical energy through a chemical reaction between lead plates and sulfuric acid. It is one of the most common and oldest types of batteries, and it is widely utilized in a variety of applications such as automotive, marine, and uninterruptible power supplies [62] Lead acid batteries are often employed in off grid or hybrid solar power systems to store solar energy. These batteries serve as energy storage devices, storing surplus solar energy created during the day and allowing it to be used when the solar panels are not producing electricity, such as at night or during cloudy weather.

Figure 25 Phoenix Lead Acid Battery

Solar energy systems that use lead acid batteries typically include solar panels that convert sunlight into power, a charge controller that manages the charging process to avoid overcharging or deep draining of the batteries, and the lead acid batteries themselves. When the solar panels generate more electricity than is consumed during the day, the extra energy is routed to the batteries for storage. When the solar panels produce more electricity than is consumed during the day, the extra energy is routed to the batteries for storage. The charge controller monitors battery voltage and optimizes the charging procedure to extend battery life. When electricity is required but the solar panels are not producing enough or none at all, the stored energy in the batteries is used to power the system.

Table 7: Generic 1kWh Lead Acid Characteristics

Electrical characteristics at (STC)	**Value**
System Voltage	12 V
System Capacity	1 kWh
Maximum Capacity	83.4 Ah
Capacity Ratio	0.403
Round Trip Efficiency	80%
Maximum Charge Current	16.7 A
Maximum Discharge Current	24.3 A
Maximum Charge Rate	1 A/Ah
Initial State of charge	100%
Minimum State of charge	40%

Lead-acid batteries are appropriate for solar energy storage due to their capacity to sustain deep discharges, their low cost in comparison to other battery technologies, and their availability in a variety of sizes and capacities to meet the energy storage requirements of diverse solar systems [63]. The battery is made up of positive and negative lead plates that are immersed in a sulfuric acid electrolyte solution. During charging, electrical energy is transferred into chemical energy, creating a chemical process that transforms lead sulphate on the plates back into lead dioxide and lead. When the battery is depleted, the reverse reaction takes place, turning lead dioxide and lead back into lead sulphate and releasing electrical energy.

2. **Lithium-Ion battery**

During charging and discharging, a lithium-ion battery (Li-ion battery) employs lithium ions to flow between a positive electrode (cathode) and a negative electrode (anode).

Figure 26: Generic Li-Ion Battery

It is widely employed in a variety of applications, such as portable electronics, electric cars, and energy storage devices [64]. Because of their high energy density, efficiency, and longer cycle life when compared to other battery technologies, lithium-ion batteries are increasingly being used in solar energy storage systems. They are ideal for storing solar energy and supplying consistent power when the solar panels are not producing electricity, such as at night or during cloudy weather. When incorporating a lithium-ion battery into a solar system, the solar panels are often connected to a charge controller, which regulates the charging process and prevents overcharging or deep discharge of the battery [65]. The charge controller guarantees that the solar energy generated by the panels is stored in the lithium-ion battery as efficiently as possible.

For solar systems, Li-ion batteries provide various advantages. They have a high energy density, which means they can store a large quantity of energy in a small space, which is especially useful for installations with limited space [66]. They also have a high charge and discharge efficiency, which allows for more effective use of the stored energy. Furthermore, lithium-ion batteries have a longer cycle life, which means they can withstand more charge-discharge cycles without experiencing substantial capacity deterioration. Another benefit of lithium-ion batteries in solar systems is their scalability and modularity. This means that additional battery units can be added as needed to increase the system's storage capacity.

Table 8: Generic 1kwh Li-ion battery characteristics

Electrical characteristics at (STC)	**Value**
System Voltage	6 V
System Capacity	1 kWh
Nominal Capacity	167 Ah
Round Trip Efficiency	90%

Maximum Charge Current	167 A
Maximum Discharge Current	500 A
Lifetime	15 Years
Initial State of charge	100%
Minimum State of charge	20%

Battery sizing:

The following equation is used for any battery sizing either for lead acid or Li ion.

$$Battery\ Capacity\ (Ah) = \frac{Total\ Watthours\ per\ day\ \times\ Days\ of\ autonomy}{Efficiency\ \ x\ 0.6\ x\ nominal\ battery\ voltage}$$

3.7 Economic Parameters

Net Present Cost:

$$NPV = \sum_{n=0}^{N} \frac{AA_{tc}}{(1+r)^n}$$

Where, N: the project period (years), r: the annual real discount rate (%)

AA_{tc} : Adjust annual total costs

Capital Recovery Factor (CRF)

$$CRF(r, N) = \frac{r \times (1+r)^N}{(1+r)^{N-1}}$$

Where N : the project period (years) , r : the annual real discount rate (%)

Levelized cost of energy (LCOE):

$$LCOE = \frac{sum\ of\ cost\ over\ lifetime}{Electricity\ generated\ over\ the\ lifetime}$$

$$LCOE = \frac{C_{ann,total}}{E_{pri}}$$

$$C_{ann,total} = CRF(i,N) \times NPC$$

Where, E_{pri} : the served annualized primary of load (kWh/year)

$C_{ann,total}$: the total annualized cost (USD).

HOMER Pro

HOMER Pro (Hybrid Optimization of Multiple Energy Resources) is a software application that is used to build and optimize micro grids and distributed energy systems. It enables users to model and simulate multiple components, such as renewable energy sources, storage systems, and traditional generators, in order to establish the most cost-effective and dependable system configuration. HOMER Pro aids in the technical and economic feasibility of various energy system designs, as well as in optimizing system performance and examining the impact of numerous factors such as energy demand, fuel pricing, and government incentives.

3.8 Summary

Research methodology chapter discusses solar energy potential in Northern Cyprus and the total load consumption of the house. It also explained the electricity load shedding in the town. This chapter explained all four configurations scenarios that have been developed in order to analyze the technical and economic feasibility of the system.

Chapter 4

RESULTS AND DISCUSSION

4.1 Base Case

Optimization results in the figure show that at the base case scenario, grid is serving the load ata Net Present Cost (NPC) of $41,523 with cost of energy (COE) $0.160 and an operating cost of $3,212. Total electricity production from the grid is 20,075 kWh/year Following graph shows monthly electricity production in MWh.

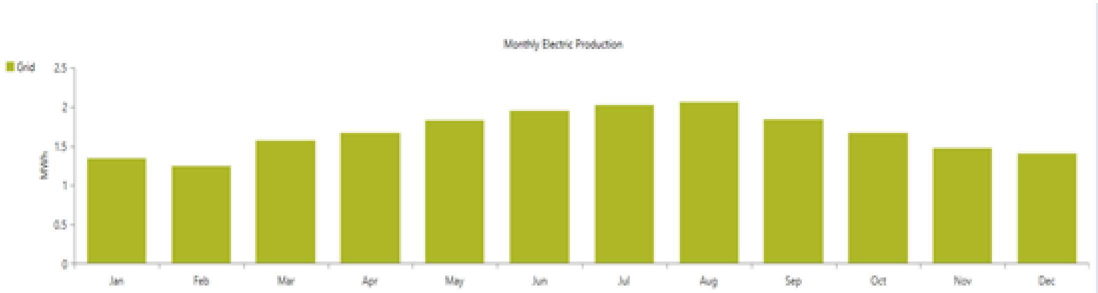

Figure 27: Monthly electricity production

All load is being met by grid electricity. The following table in figure 28 shows monthly energy purchased from the grid and energy charged monthly. In the base case we have only grid and that will meet the load of the house for four people. The total load of the house is 20,075 kWh/year and the grid can meet the all the load. If there is a grid outage in the area, the grid will not be able to meet the load at that specific hour.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge $	Demand Charge $
January	1,346	0	1,346	8	$215.37	$0
February	1,245	0	1,245	7	$199.13	$0
March	1,569	0	1,569	8	$251.10	$0
April	1,663	0	1,663	9	$266.08	$0
May	1,831	0	1,831	9	$292.89	$0
June	1,943	0	1,943	9	$310.82	$0
July	2,027	0	2,027	12	$324.33	$0
August	2,060	0	2,060	11	$329.61	$0
September	1,840	0	1,840	10	$294.33	$0
October	1,670	0	1,670	9	$267.24	$0
November	1,470	0	1,470	9	$235.21	$0
December	1,412	0	1,412	7	$225.88	$0
Annual	20,075	0	20,075	12	$3,212.00	$0

Figure 28: Grid electricity charges per month

As in the proposed system cases, the grid outage is in November, December, January, and February and for one hour that is at 7:00 PM. After adding an outage in the system, when the proposed system is calculated the Homer system, it doesn't find any feasible system for that house because, during the outage, there is no backup power supply to meet the load at outage hours.

Therefore, we need backup power supplies like a renewable source e.g., Solar PV or a battery, or we can add both renewable source and the battery to meet the load. So that's why we have added a renewable energy source in the system in the next case.

4.2 Grid and Solar System - Case -2

HOMER optimization results show that NPC for PV and grid system is $15,327 and COE is $0.0365 with operating cost $399.79/year and a simple payback period is 6.2 year. The optimal system consists of 16.2 kw PV, 8.23 kw Converter.

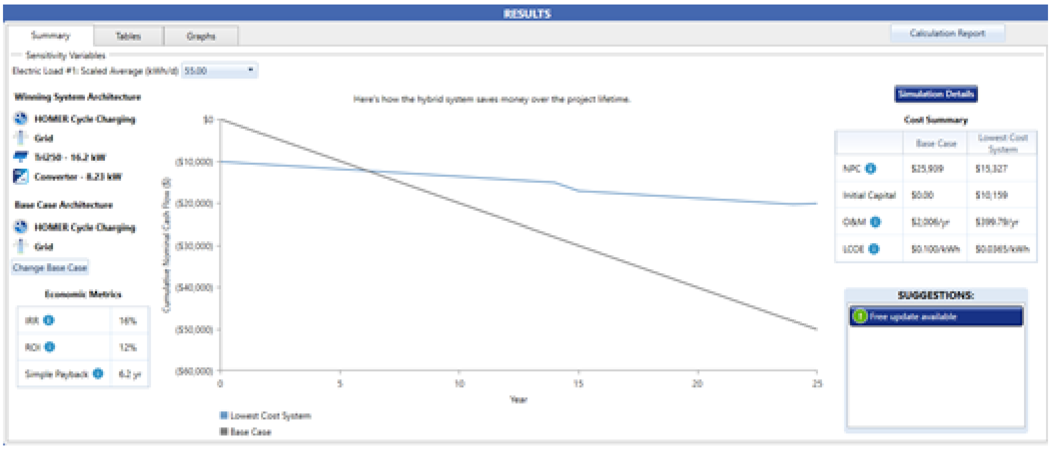

Figure 29: Optimization Results

The solar panel meet only daytime load because it only produces electricity during daytime. At night-time, grid serves the load.

Optimization Results

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

Architecture			Cost				System		Tr250		Converter		Grid
Tri250 (kW)	Grid (kW)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Capital Cost ($)	Production (kWh/yr)	Rectifier Mean Output (kW)	Inverter Mean Output (kW)	Energy Purchased (kWh)
16.2	999,999	8.23	$15,327	$0.0365	$399.79	$10,159	65.7	0	8,102	25,215	0	2.44	11,159
	999,999		$25,909	$0.100	$2,006	$0.00	0	0					20,063

Figure 30: Optimization results

The excessive electricity that is produced during daytime, is not being stored because there is no storage. Therefore, this excess electricity is sold back to the grid at rate of $0.05/kWh.

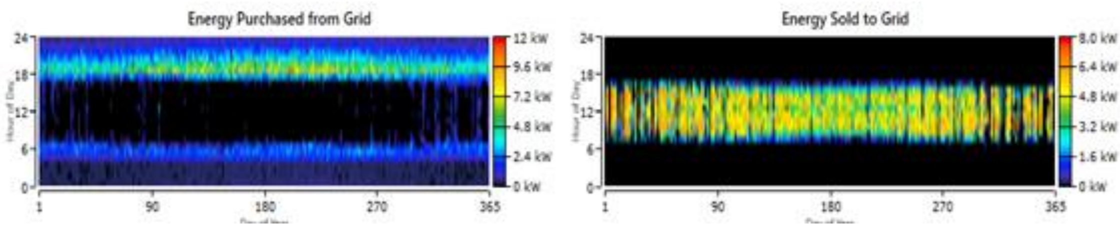

Figure 31: Grid electricity sold and purchased

Figure 32 show the monthly electricity purchased, sold and energy charges. We can see that the total energy charge (Bill) is reduced due to net metering.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge $	Demand Charge $
January	873	895	-23	8	($1.13)	$0
February	735	933	-198	7	($9.90)	$0
March	831	1,168	-337	8	($16.84)	$0
April	882	1,139	-257	9	($12.83)	$0
May	951	1,154	-203	9	($10.14)	$0
June	1,012	1,047	-35	9	($1.76)	$0
July	1,066	1,108	-42	12	($2.08)	$0
August	1,088	1,096	-8	10	-$0.4	$0
September	979	1,112	-133	10	($6.66)	$0
October	917	1,142	-225	9	($11.25)	$0
November	903	865	38	9	$3.81	$0
December	922	785	137	7	$13.68	$0
Annual	11,159	12,444	-1,285	12	($55.51)	$0

Figure 32: Grid electricity sold, purchased, energy charges

And if there is an outage in the grid during the night-time at 7:00 PM. This system cannot meet the load because solar PV is only for the daytime slot. Therefore, the current system cannot meet the load during load-shedding hours, so there is a need to add storage in the system so that it can serve the load at night time during outages.. In the next case, we have added only storage in the system so that the grid can charge the battery and it can be used during load shedding.

4.3 Grid with Battery Case-3

The optimal system is 21 kWh Batteries with 5.06 kW converter with a net present cost $56,417 and a cost of energy to $0.217 with operating cost $3,941.

Architecture							Cost		
			1kWh LA	Grid (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)
			21	999,999	5.06	CC	$56,417	$0.217	$3,941

Figure 33: Optimal PV system

Cash flow for the 25-year lifetime of the project. In this case, the net present cost is too high because of higher operating and replacement costs. During the load-shedding hours, energy stored in the battery serves the load. The following graph shows the state of charge of the battery.

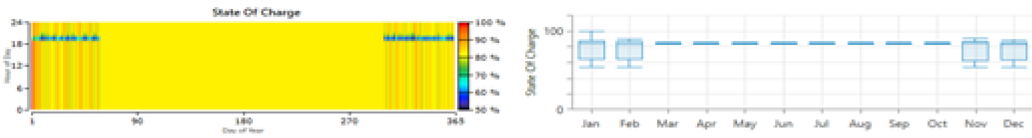

Figure 34: Battery state of charge

4.4 Grid Connected Hybrid Solar System – Case-04

1. Using Lead Acid Battery:

The optimization results show that 17 kw PV, Grid, 21 kWh Lead Acid Battery and 8.69 kW Converter make a system that can meet the load during day and night. The system is optimal because of lowest net present cost $24,547 and cost of energy of $0.0563.

Architecture				Cost				System	
Tri250 (kW)	1kWh LA	Grid (kW)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
17.0	21	999,999	8.69	$24,547	$0.0563	$748.52	$14,870	69.1	0

Figure 35: Optimization Results of Hybrid System

During the day, PV panels generate excess electricity that is being sold to the grid. During the night time, the system uses electricity from the grid rather than battery because grid cost is lower than battery cost. The following figure shows the total electricity production and consumption.

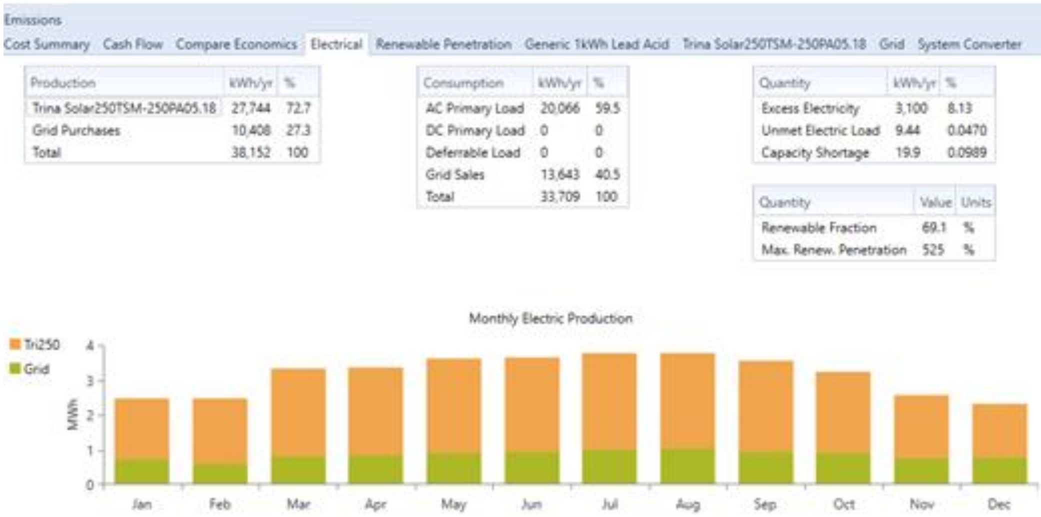

Figure 36: Electricity Production and Consumption

Net Metering and Electricity charges:

The system is selling excess electricity back to the grid at the rate of $0.05/kWh. The figure 37 shows yearly electricity purchased and sold to the grid and electricity charges per month.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge $	Demand Charge $
January	738	811	-73	8	($3.66)	$0
February	619	885	-267	7	($13.34)	$0
March	825	1,280	-456	8	($22.79)	$0
April	863	1,307	-444	9	($22.22)	$0
May	915	1,393	-479	9	($23.93)	$0
June	962	1,320	-358	9	($17.88)	$0
July	1,015	1,370	-355	12	($17.75)	$0
August	1,050	1,301	-251	10	($12.56)	$0
September	965	1,250	-285	10	($14.26)	$0
October	914	1,228	-314	9	($15.71)	$0
November	758	791	-32	9	($1.62)	$0
December	785	706	80	7	$12.76	$0
Annual	10,408	13,643	-3,235	12	($152.98)	$0

Figure 37 Grid Electricity Charges

2. **Using Lithium-ion Battery:**

In this case, optimal system is a 17 kw PV system, 146 kWh Lithium-ion battery and 6.37 kW converter. This system shows a very high net present cost due to high cost and large size of lithium-ion batteries. The net present cost is $89,207 and cost of energy for the optimal system is $0.293.


Export...

Optimization Results

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

Architecture							Cost				System	
				Tri250 (kW)	1kWh LI	Grid (kW)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
				17.0	146	999,999	6.37	$89,207	$0.293	$1,602	$68,493	98.3	0

Figure 38: Optimal system with Li-ion battery

Electricity production and consumption:

The following table shows the summary of how much electricity is produced and consumed during the operation of proposed system.

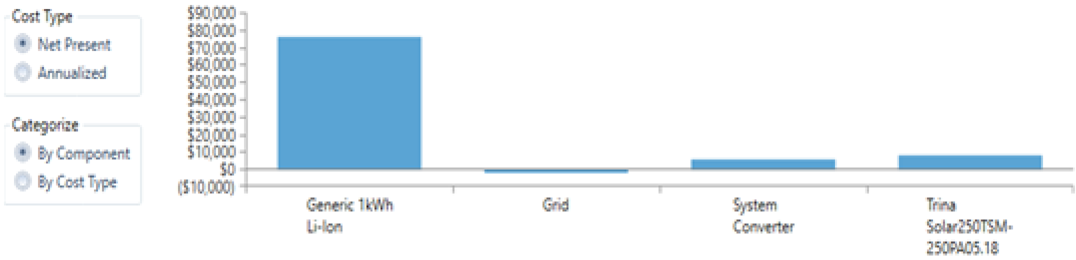

Figure 39: Proposed System Costs by component

Figure 40: Electricity production and consumption graph

Optimal System

The optimal system configuration is Grid connected solar system which shows a $24,547 net present cost and a cost of energy $0.0563. The system consists of 17 kw solar panels, 21 kWh Lead Acid batteries with 8.69 kW converter. The system capital cost and operating cost are less than lithium-ion battery configuration.

Table 9: Proposed System NPC and COE

Cases	**NPC**	**COE**
1. Only Grid	$41,523	$0.160
2. Grid + PV	$15,327	$0.0365
3. Grid (outage) + Battery	$56,417	$0.217
4. Grid (outage) + PV + Battery storage (LA)	$24,547	$0.0563
5. Grid (outage) + PV + Battery storage (Li-ion)	$89,207	$0.293

GHG Emissions

The following figure shows GHG emissions per year for the optimal system.

Quantity	Value	Units
Carbon Dioxide	6,578	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	28.5	kg/yr
Nitrogen Oxides	13.9	kg/yr

Figure 41: GHG Emissions of optimal system

Chapter 5

CONCLUSION

This chapter presented the HOMER Pro software simulation results for each configuration for the proposed system. Solar PV systems can only provide energy during the daytime when the sun is available. So, battery storage is necessary to meet the household load demand. As shown in Table 9, 2^{nd} configuration which is Grid grid-connected PV system shows the lowest net present cost and lowest cost of energy. It means that this system is the most feasible for a single-family house. However, the NPC of a hybrid system with a lead acid battery is less than the system with a lithium-ion battery. A lithium-ion battery is more expensive than a lead-acid battery. For a single-family house, a lead acid battery is more suitable than a Li-ion battery. The lithium-ion battery system has a high initial capital investment along with a high operating cost. The optimal system emits less emissions than other system configurations.

The conclusion of this work presents that the proposed system shows many benefits like reduction in greenhouse gas emissions, reduction in electricity price, reduction in electricity bills, and reduced fuel price. If the system is simulated without Grid outage then, HOMER Pro can compare the economics of the system by calculating the payback period for each configuration. An average payback period for an optimal system is 3 years which means that after 3 years initial investment would be covered and the system will be making savings after this period. The limitations included are that it didn’t consider the debt, tax and depreciation values. In future, an MCA mechanism can be developed to select the best components for the optimized system.

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APPENDIX

Economic Parameters

Components	Parameters	Values
Main Grid	Grid Power Price	0.16 $/kWh
	Grid Sell back Price	0.05 $/kWh
Lead Acid Battery	Battery Type	Lead Acid
	Nominal Capacity	1 kWh
	Capital Cost	$200
	Replacement Cost	$170
	Operational Cost	$10
Lithium Ion Battery	Battery Type	Lithium ion
	Nominal Capacity	1 kWh
	Capital Cost	$400
	Replacement Cost	$360
	Operational Cost	0
PV System	Panel Type	Flat Plate
	Rated Capacity	16 kW
	Efficiency	13 %
	Capital Cost	500 $/kW
	Replacement Cost	300 $/kW
	Operational Cost	0 $/Year/kW
AC/DC Converter	Inverter Input Efficiency	95 %
	Rectifier Input Efficiency	95 %
	Capital Cost	250 $/kW
	Replacement Cost	200 $/kW
	Operational Cost	50 $/Year/kW

General Specifications of the Trina Solar

ELECTRICAL DATA @ STC	TSM-230 PC/ PA05	TSM-235 PC/ PA05	TSM-240 PC/ PA05	TSM-245 PC/ PA05
Peak Power Watts-P_{MAX} (Wp)	230	235	240	245
Power Output Tolerance-P_{MAX} (%)	0/+3	0/+3	0/+3	0/+3
Maximum Power Voltage-V_{MP} (V)	29.2	29.3	29.7	30.2
Maximum Power Current-I_{MPP} (A)	7.90	8.03	8.10	8.13
Open Circuit Voltage-V_{OC} (V)	37.1	37.2	37.3	37.5
Short Circuit Current-I_{SC} (A)	8.53	8.55	8.62	8.68
Module Efficiency η_m (%)	14.1	14.4	14.7	15.0

Values at Standard Test Conditions STC (Air Mass AM1.5, Irradiance 1000W/m², Cell Temperature 25°C).
Power measurement tolerance: ±3%