OPTIMAL MIX OF A SOLAR, WIND, AND FUEL CELL HYBRID RESIDENTIAL SYSTEM

SUSTAINABLE ENVIRONMENT AND ENERGY SYSTEMS

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Abstract

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HYBRID RESIDENTIAL SYSTEM

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M. Sc., Sustainable Environments and Energy Systems

Supervisor: Assoc. Prof. Murat Fahrioglu

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Nowadays, supplying electrical power using renewable energy systems faces problems due to the high cost and unreliability of those systems. With the variability of renewable energy sources, a possible way to provide electricity is by combining different renewable sources in one hybridized system. This study is about optimizing and testing the feasibility of different hybridized systems including solar, wind, and fuel cell systems. The study will include on-grid and off-grid optimal solutions for a case study in Middle East Technical University (Northern Cyprus Campus) on a residential scale for a typical household on this isolated island. The case will include models of solar panels, wind turbines, and fuel cell systems of different sizes and power outputs to result in an optimal combination showing the Levelized Cost of Electricity, Net Present Cost, and electricity production of each of the renewable sources. Equations from the methodology are inputted into HOMER Software and the software does thousands of simulations to come up with the optimal result. The lowest LCOE results for an off-grid solar/wind/fuel cell system is 0.3418 $/kWh, and lowest LCOE for an on-grid is 0.118 $/kWh with only a

solar panel and the electricity grid. However, more cost and location assumptions are made throughout the research to yield in different LCOEs. Emissions are also taken into consideration in this study with penalties for carbon dioxide. Since this is a study on a household demand, the emissions per year are not as high as large-scale electricity production.

OZ

Günümüzde, yenilenebilir enerji sistemlerini kullanarak elektrik enerjisi tedariği, bu sistemlerin yüksek maliyet ve güvenilmezliği nedeniyle sorunlarla karşı karşıya bulunuyor. Yenilenebilir enerji kaynakları potansiyeli ile, elektrik sağlamak için olası bir yol, farklı yenilenebilir kaynakları bir melezleştirilmiş sistemde birleştirmektir. Bu çalışma, güneş, rüzgar ve yakıt hücresi sistemleri de dahil olmak üzere farklı melezleştirilmiş sistemlerin fizibilitesini optimize etmek ve test etmek ile ilgilidir. Çalışma, Orta Doğu Teknik Üniversitesi'nde (Kuzey Kıbrıs Kampusu) bir vaka çalışması için şebekede ve şebekeden bağımsız optimal çözüm getirecektir. Bu yazıda, güneş panelleri, rüzgar türbinleri ve yakıt hücresi sistemleri için yeni bir model öneriyoruz. Bu yazıda, güneş panelleri, rüzgar türbinleri ve yakıt hücresi sistemlerinin optimal kombinasyonunu öneriyoruz. Metodolojiden elde edilen denklemler HOMER Yazılımı içine alınır ve yazılım optimal sonuçları elde etmek için binlerce simülasyon yapar. Şebekeden bağımsız bir güneş / rüzgar / yakıt hücresi sistemi için en düşük LCOE sonuçları 0.3418 $ / kWh, şebekede en düşük LCOE ise sadece bir güneş paneli ve elektrik şebekesi ile 0.118 $ / kWh'dir. Bununla birlikte, farklı LCOE'ler üretmek için araştırma boyunca daha fazla maliyet ve yer varsayımları yapılmıştır. Bu çalışmada karbon dioksit için verilen cezalar da dikkate alınarak emisyonlar da dikkate alınmıştır. Bu büyük ölçekli bir elektrik üretimi olduğundan emisyon kadar yüksek değildir.

Dedication

I dedicate my work to my family for the continuous love and support.

Acknowledgments

First and foremost, I would like to thank the person that gave me unconditional support throughout my 2 years in METU NCC. Whether it was providing me with personal transportation from my old household in Lefkosa, or continuously checking up on my progress, Dr. Murat Fahriouglu, my thesis advisor, was a true father figure.

I appreciate the efforts put by all the professors in the Sustainable Energy department. Regards to Dr. Aylin Topal for the SEES 501 course, Dr. Murat Fahrioglu for the SEES 502 course, Dr. Bertug Akintug for the SEES 503 and SEES 594 courses, and Dr. Aysu Kentel for the SEES 593 and SEES 596 courses. The diligence of the previous head of SEES, Dr. Ali Muhtarioglu, and the current head, Dr. Carter Mandrik, is shifting the department towards a better reputation and more successful future. Those professors and courses shed light on the way towards a successful master's thesis and taught me a lot about organization and time management.

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Chapter 1 - Introduction

The generation of energy is necessary to ensure a step-up in the quality of life and boost elements that our society depends on. Due to the escalation in environmental impacts and costs of conventional methods of producing electricity, researchers and scientists are starting to have an appetite for renewable energy sources (RES) [1]. An appetite that not only satisfies the economic and social factors, but includes the environmental aspect as well [2]. It is debatable whether or not the electricity production can keep growing without putting an effort to stabilize it. In any case, there is no doubt that this form of energy demand is skyrocketing. Clearly, if the demand for electricity keeps increasing in this manner, then the generating capacity should be in direct proportionality. Renewable energy sources, being naturally abundant with nearly no polluting effects, can provide a solution to this problem. According to the World Bank in 2012, there was more than 26,500 TWh of energy generated. Energy production was displayed in the form of a pie chart, which clearly shows more than 40% for coal, 16% hydro, 11% nuclear, 4.7% renewable sources, and 4.1% oil. It is to be noted that the RES electricity generation have been increasing for the past two decades. As 4.7% does not account for much of the total energy produced, renewable sources were only at 2% and grew up to 4.7% in 2012 [3]. A promising way of including more renewable sources in the worldwide production is introducing renewable energy micro grids (REMG). These micro grids are, basically, grids that have one or more local source with or without a storage unit. Authors Evans et al. argue that implementing RES to large-scale energy production is at a disadvantage due to two reasons; The variability or inconsistency of renewable sources, and the research that lead to the fact that specific cost of electricity is higher for RES when used in mass energy production [4]. Due to these challenges, researchers and decision makers prefer hybrid systems that have at least one conventional energy production method along with less reliable back-up renewable source [5].

For a Hybrid or Grid-Tied REMG, the parameters that are mainly focused on are maximizing the islanding fraction of time and total feasibility of the system. It is extremely dependent on the location in which RES is located. Studies suggest that REMG are most feasible in isolated communities where the potential for RES is very high and the electricity from the grid is too unreliable, expensive, or not present at all. These places are usually categorized under rural areas, islands, and developing countries [6].

As much as it is desired for REMG to become the dominant alternative for environment-polluting methods of power extraction, the challenges associated with the technical and economic aspects still limit the potential of such systems. For example, solar energy is most effective on a sunny day with clear skies. Wind energy can only be utilized when there are enough winds travelling at a specified minimum speed to turn wind turbines. The variability and instability of renewable sources can limit the total usable energy produced via their different means. Therefore, a solution is combining all the perks of renewable sources into one system with a storage mechanism that enables more use of the greener energy.

Objective of Study

The main objective of this thesis is to implement a hybrid system that consists of solar, wind, and fuel cells to reduce the use of non-renewable resources and making this system economically, environmentally, and socially acceptable. This broad objective can be narrowed down into two sub-objectives to give a better understanding of what this study will pursue.

First, acknowledging what is available in literature regarding RES and REMG and building upon it by expanding the usage of these systems in different locations to utilize the limited electricity from non-renewable sources, and partially depend on renewable sources of energy. The study will include calculations of Net Present Cost, Levelized Cost of Energy, and RES fraction for different types of electricity connections.

The second objective is to contrast the feasibilities of all the different options including one or more PVs, wind turbines, or fuel cells. The ultimate goal of doing so is to implement a Hybrid RES that can be used in the case study in METU NCC along with statistically generated typical meteorological year (TMY) data values.

Chapter 2 - Literature Review

In this chapter, an overview of the worldwide energy demand will be discussed. Then, the applied renewable technologies used in this research that are combined in a power generating system will be examined in terms of general description, history, and different types. After that, the current knowledge about Hybrid REMGs will be discussed in two subsections. The first subsection will focus on energy storage systems in their various forms and will determine according to facts withdrawn from literature which energy storage systems are most appropriate for the study. The second subsection discusses different configurations for the REMG, which mainly rotate between PV, wind, and fuel cells.

Overview of Energy Demand

Ever since the beginning of the 20th century, fossil fuels became the dominant source of energy to meet the world's annual energy demand. Year after year, the world's energy consumption is increasing exponentially due to a trend towards a more superior quality of life. The extensive use of fossil fuels causes various pollutant gases to be spread between the atmosphere and stratosphere. Such gases are called greenhouse gases and are believed to be the leading cause of what is known as Global Warming [7]. Governments now are not only pressured to meet the energy demand of the world, they also need to find new and efficient ways to decrease greenhouse emissions. During the economic crisis in 2007 and 2008, oil prices became the highest to be ever recorded after the Second World War. Also, more evidence during the crisis showed that the main cause of global warming and climate change is the burning of fossil fuels. The reasons mentioned stress the importance of dealing with the swift rise in demand with limited supply [9]. Different regions need to start looking at energy alternatives to reduce greenhouse emissions and the gap of energy demand that is still expected to increase in the future. Figure 1 shows a typical carbon cycle to indicate the levels of the greenhouse gases in different forms of life.

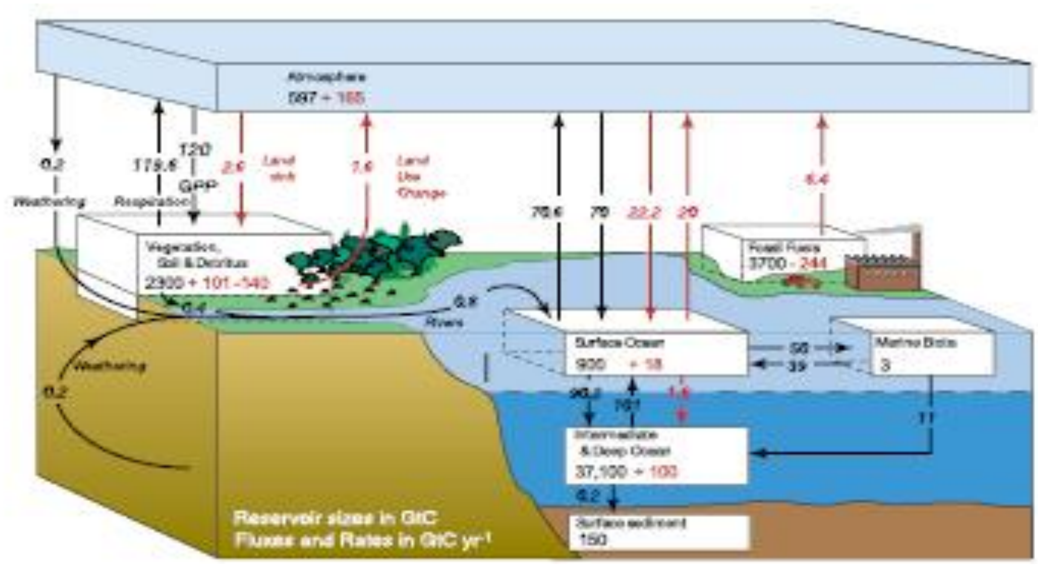

Figure 1: Carbon Cycle Hazards [8]

In spite of the economic crisis in 2008, the worldwide energy consumption is expected to grow by an average of 1.4% each year till the year 2035. According to statistics, this means that the energy consumption is expected to increase by just lower than 50% from the beginning of 2007 till the end of 2035 [9]. Countries that have a fast growing economy are the countries that can have dramatic effects on energy consumption. For example, up until 1990, China and India consumed 10% of the total world energy consumption. Up till 2007, they both had shares that doubled to reach 20%, and if they keep growing in economy, it is predicted that 30% of the world consumption would be shared between them. On the other hand, countries like the United States of America are expected to go down from 21% in the beginning of 2007 to 16% in the end of 2035 due to improvements in equipment, infrastructure, and technologies [10]. Figure 2 shows the worldwide energy consumption from 1990 and forecasts the consumption till 2040. OECD is the Organization for Economic Cooperation and Development, and it is represented by 34 democracies that work together to improve economy and sustainability. The figure shows stable energy consumption by OECD while non-OECD has growing consumption after the year 2015.

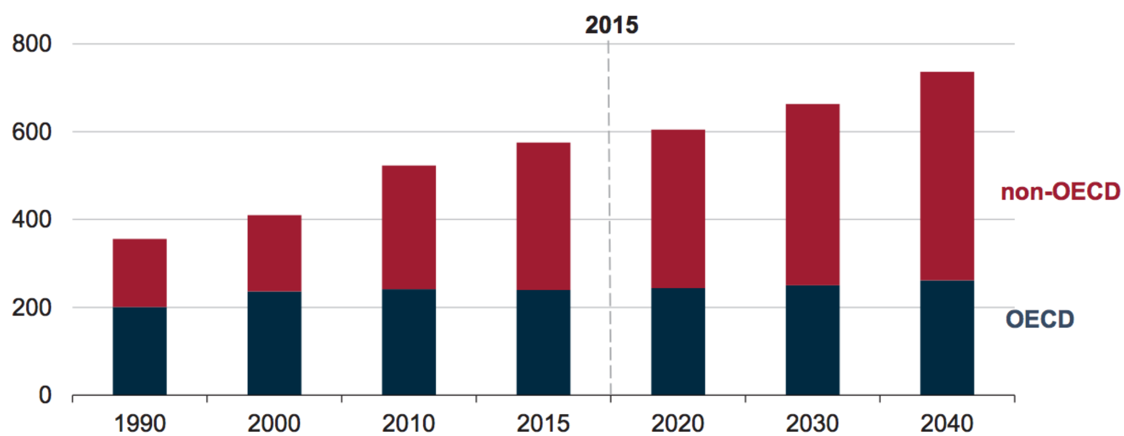

Figure 2: World Energy Consumption in OECD and non-OECD (Quadrillion Btu) [11]

A problem with oil supply is that it is unevenly distributed around the world. This tampers with the stability of energy supply even with conventional methods due to political disagreements or natural causes. Moreover, another problem with oil and other fossil fuels is the constant need to find balance between the predicted demand and the new discoveries. Figure 3 explains the oil supply and demand trends from the year 2002 till the end of 2016 and projects an approximation for the foreseen future. The figure implies that the year 2015 and 2016 were a success due to larger number of stock available. However, the forecast for 2017 shows that the balance is almost neutral which means that the demand is equal to the supply. A neutral balance does not necessarily indicate an improvement. The balance is reached because of an increase in oil production amounts.

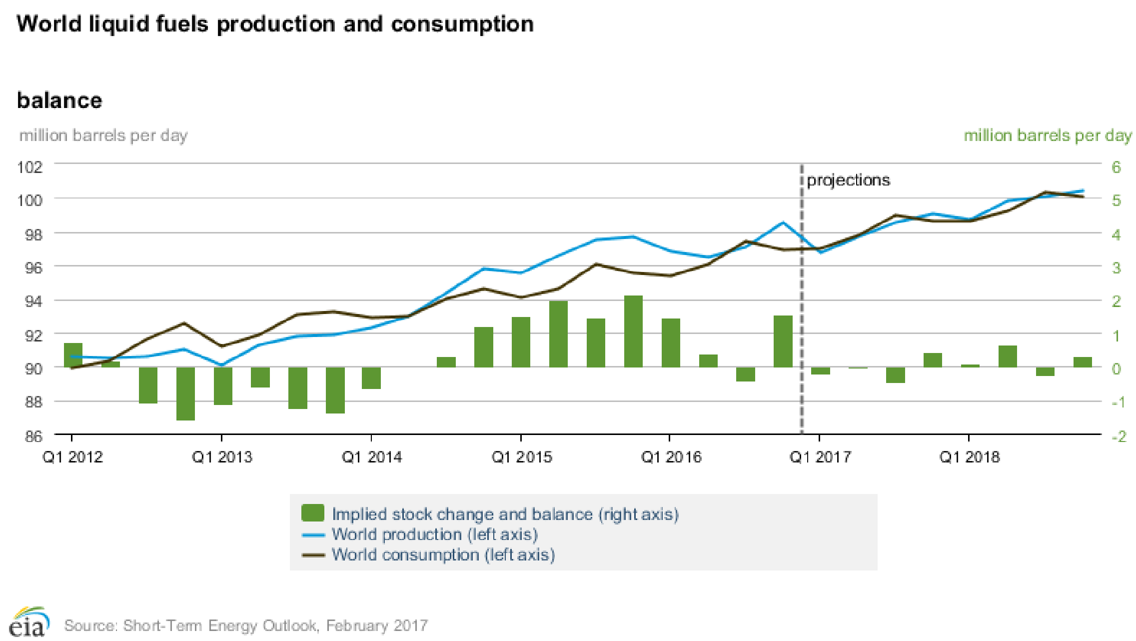

Figure 3: Oil Supply, Demand, and Stock [12]

The following section will explain the history, general description, and different types of photovoltaic cells.

Photovoltaic Cells

History

The term photovoltaic is from Greek origins and translates to “electrical light”, and it has been used since 1849. Photovoltaic Cells are devices that convert solar irradiation into direct current electrical energy, and the only fuel that is needed in this type of renewables is basic sunlight. A French scientist named Alexander Becquerel in 1839 first recognized the photovoltaic effect. However, Charles Fritts was the first to build a solar cell in 1883 by coating the semiconductor with a layer of gold to create junctions. Fritts’s new PV creation only had 1% efficiency. In the 1950’s, more extensive research was made and took around 20 years to start with the commercial production stage, which was after the 1970s oil crisis [13]. The following table explains the stages of development of PV cells from their early years until 2016.

Table 1: History and Development of PV Cells [14], [15], [16]

Year	Development
1839	French experimental physicist, Becquerel, experiments with electrolytic cells and 2 electrodes to discover the photovoltaic effect.
1883	The first solar cells with selenium wafers are described by Charles Fritts.
1905	Albert Einstein publishes paper on relativity and theory of photovoltaic effect.
1951	Production of single-crystal germanium cell
1954	First high power silicon photovoltaic cell by Bell Labs.
1963	242 W PV array was installed on a lighthouse in Japan, the largest PV installation yet.

1966	NASA launches an observatory with 1 kW PV array.
1968	Launching of OVI-13 with solar panels.
1972	• Solar Power Corporation established.
	• Cadium Sulphide PV system in Niger,France.
1976	Kyocera Corp. silicon ribbon solar modules
1982	• Worldwide PV supply became more than 9.3 MW.
	• 1 MW plant with 108 dual-axis trackers went online in California.
1984	30 kW solar system connected to the public electric grid in Southampton, England.
1989	PVcells with thin-film established.
1990	100,000 Solar Roofs program in Germany.
1994	Japan begins 70,000 Solar rooftops.
2002	NASA remotely control solar-powered aircraft.
2004	Only 5 major companies control 60% of the PV market.
2009	Announced capacity of PVs became 24 GW.
2015	Flexible printed PV cells enter the market with 20% power conversion efficiency.
2016	The discovery of sunless solar power with nanomaterial.

General Description

When sunlight irradiates on a photovoltaic cell, photons that are absorbed evict electrons from their atoms. Electrons are then obligated to move along the borders of the cell, filling and creating holes within it. This unique movement of electrons in the cell generates electricity, and the process of converting sunlight energy into electrical energy is called the photovoltaic effect. Electrons are forced to flow to the N-type material (n-region) where they go through an external circuit and provide power to a given load, and the holes are dragged to a P-type material [17]. Figure 4 provides a visual description.

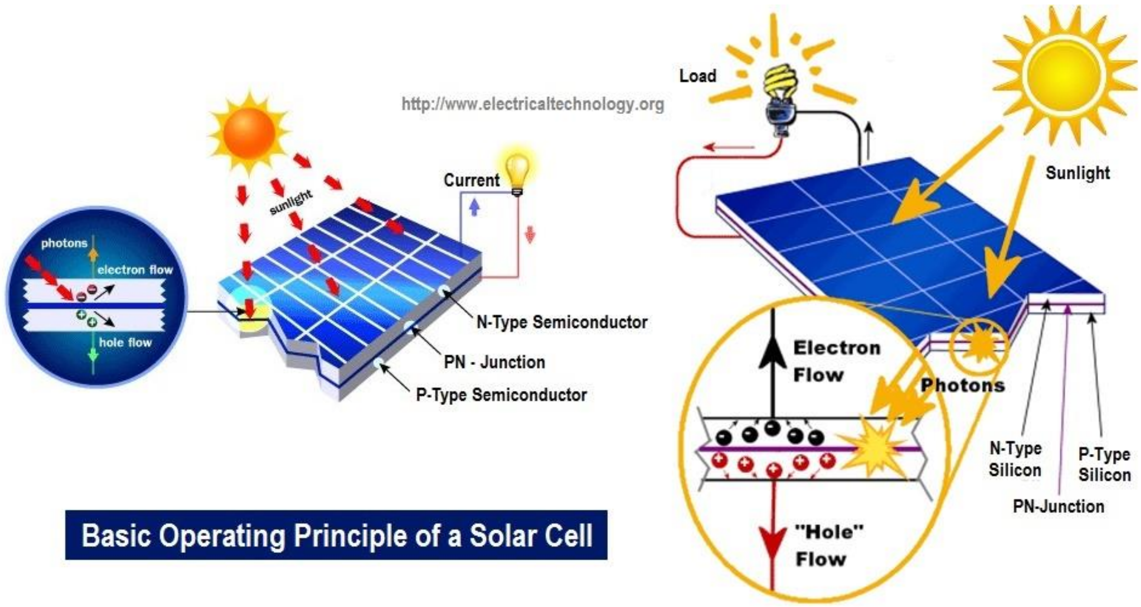

Figure 4: Operating Principle of PV Cells [18]

Since each cell on its own does not produce more than 2 W at 0.5 Volts, it is important to build connections between PV cells to produce higher power. The connections can be in series, parallel, or both series and parallel to produce any range of power from a couple of Watts to hundreds of Watts. The following figure illustrates the configuration of a cell, module, and array.

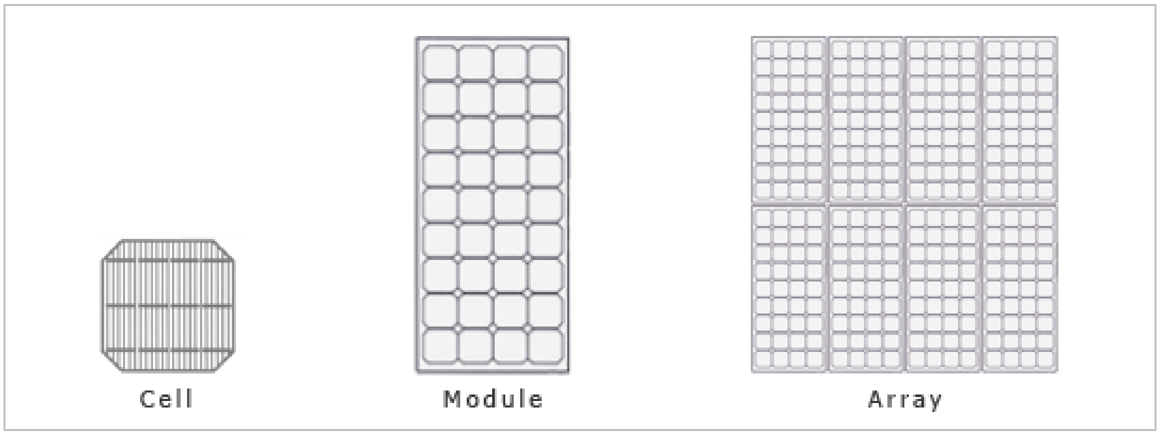

Figure 5: PV Cell, Module, and Array

PV Cell Types

Photovoltaic cells can be classified based on the technologies used to manufacture them. Mainly, the two categories of technology used in manufacturing fall under crystalline silicon, the most commonly used one, or thin film, the newer thriving technology. The following figure shows the available technology till 2015.

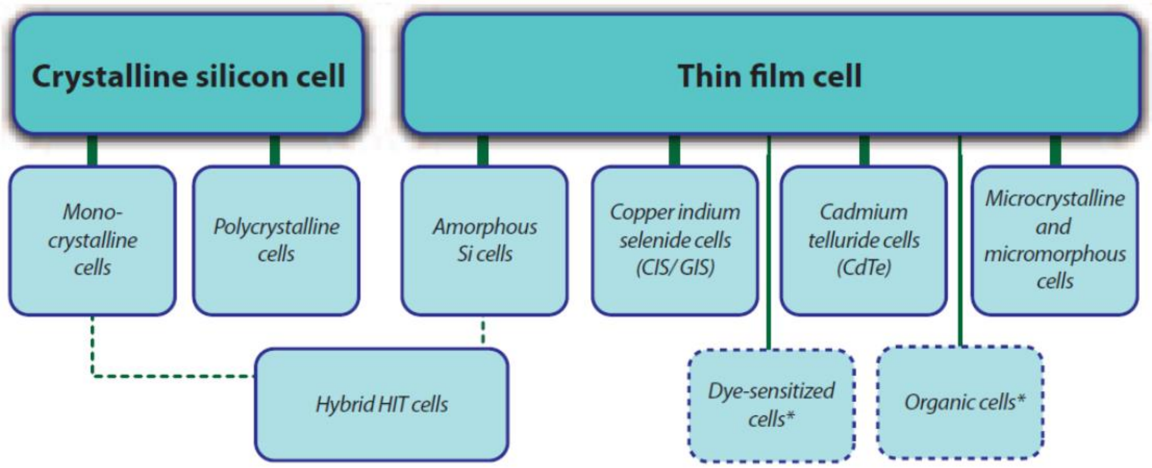

Figure 6: Types of PV Cells [20]

Crystalline cells are produced using ultra-pure silicon, which is the same material used in the production of chips in semiconductors. An average of 170 microns of silicon wafers are used to manufacture a single PV cell. The quantity of silicon wafers varies between 150 to 200 microns. The advantage in this type of PV cells is the availability of silicon on Earth. On the other hand, the other type of PVs is manufactured by applying up to 2 micrometers of semiconductor on glass or stainless steel sheets. Compared to the process and the manufacturing equipment, the cost of the material itself is nearly costless due to the degree of thinness of the layers of the material [20]. Shares of thin film PVs started increasing in the past 5 years because they are more flexible and easier to install and operate. The following table shows the difference in efficiencies of the two types of PV cells.

Table 2: Efficiencies of different PV cells [25]

Type	Standard Efficiency %	Maximum Recorded Efficiency %
Mono-crystalline (sc-Si)	15-20	23.4
Multi-crystalline (mc-Si)	13-16	17.3
Copper Indium Diselenide (CIS)	10	12.2
Micro morph silicon (μm-Si)	9-11	12
Cadmiumtelluride (CdTe)	8-10	10.9
Amorphous Silicon (a-Si)	6-8	8.3
Dye sensitized	4-8	8
Organic	2-5	5

Much like this section, the following section will address wind energy in the same manner.

Wind Energy

History

Since the start of recorded history, literature has shown that mankind harvested wind energy in various forms, whether it was for propelling ships along the Nile river in 5000 B.C., pumping water from small windmills in China and grinding grain in the Middle East and Persia by 200 B.C., or food production in Europe and the Middle East by the 11th century. New ways of using wind energy eventually spread around the globe, and the most common way of harvesting this type of energy is using a wind turbine [22]. Table 3 will display the important historical development of wind turbines in terms of mechanical and electrical purposes.

Table 3: History and Development of Wind Turbines [22], [23], [24]

Year	Development
1887	James Blyth created the first wind turbine with a 10m height for electrical purposes.
1908	72 wind power systems with capacity of 30 MW across Denmark.
1931	Vertical and horizontal axis wind turbines used with 100 kW capacity, 32 m high, and 32 % load factor.
1941	The first MW-sized turbine with 1.25 MW.
1978	First multi-MW turbine made in Germany with 2 MW capacity.
1980	• LCOE of wind power is 0.38$/kWh
	• Denmark sites offshore wind turbines.
	• Commercial wind rotors have 75 kW capacity and 17 m in diameter.
1981	• Second wind farm in the U.S. supplying 10 MW to more than 8,500 homes.

	• Credit taxes for wind turbines in California.
1984	15 wind farms in the U.S. supplying 146,000 homes.
1991	First offshore wind farm in Denmark with 11 wind turbines and 450 kW capacity.
1998	Global wind capacity is 10.2 MW
2000	• 97 wind farms online in U.S. supplying 592,000 homes with 2.55 MW.
	• The largest recorded order of wind turbines (1,800 Vestas wind turbines).
	• Global wind capacity is 17.4 MW
2002	Global wind capacity reaches 31.1 MW.
2008	• 2,416 wind farms across the U.S. and U.K. supplying 8 million homes combined.
	• Global wind capacity is 120.3 MW.
	• More investment tax credits applied in the U.S.
2012	• Wind power is 75 GW in China and 3 GW in Britain.
	• Denmark has 30% of its demand from wind turbines.
	• World wind capacity is 282.6 MW
2016	4.87 GW worldwide wind generation capacity.

General Description

Certain factors like the uneven irradiation of the sun on Earth's atmosphere, constant rotation of the Earth, and the irregularities of Earth's surfaces contribute to different levels of wind intensity. Terrains, vegetative covers, and water bodies adjust wind flow patterns. Modern wind turbines are used to harvest this type of motion energy to create electricity. The operation of wind turbines depends on a simple principle. Wind energy turns two or three blades that act as propellers that work around a rotor. A connection between the rotor and a main shaft spins a generator, which, in turn, generates electricity. In simpler words, wind turbines operate in the exact opposite fashion of an electric fan. The fan uses electricity to provide wind while wind turbines use the kinetic energy in wind to provide electricity [26. Figure 7 shows the components that can be found in a typical horizontal axis wind turbine.

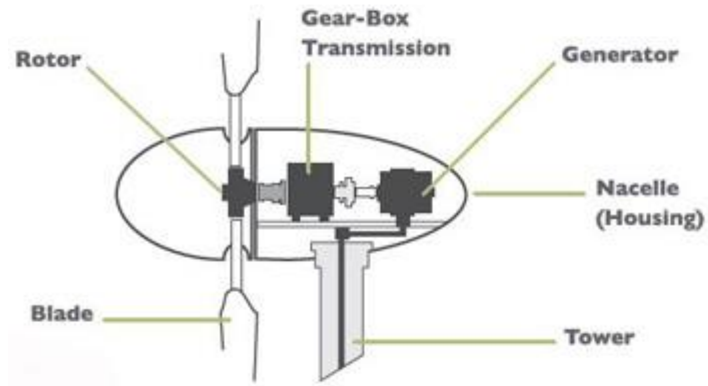

Figure 7: Components of Wind Turbines [27]

The main components found in wind turbines are:

1. Rotors or Blades; responsible for converting wind energy to rotational energy in the shaft.
2. Drive train; includes a generator and gearbox.
3. Tower; supporting drive train and rotors.

Other components that can be found in a horizontal axis wind turbine include electrical cables, controls, and interconnection and ground support equipment. These components are used to enhance the performance of the wind turbine. Figure 8 explains the growth of wind power since 2001 till 2016. The exponential growth in installed wind capacity only proves that cultivating this power source is reliable and economically acceptable.

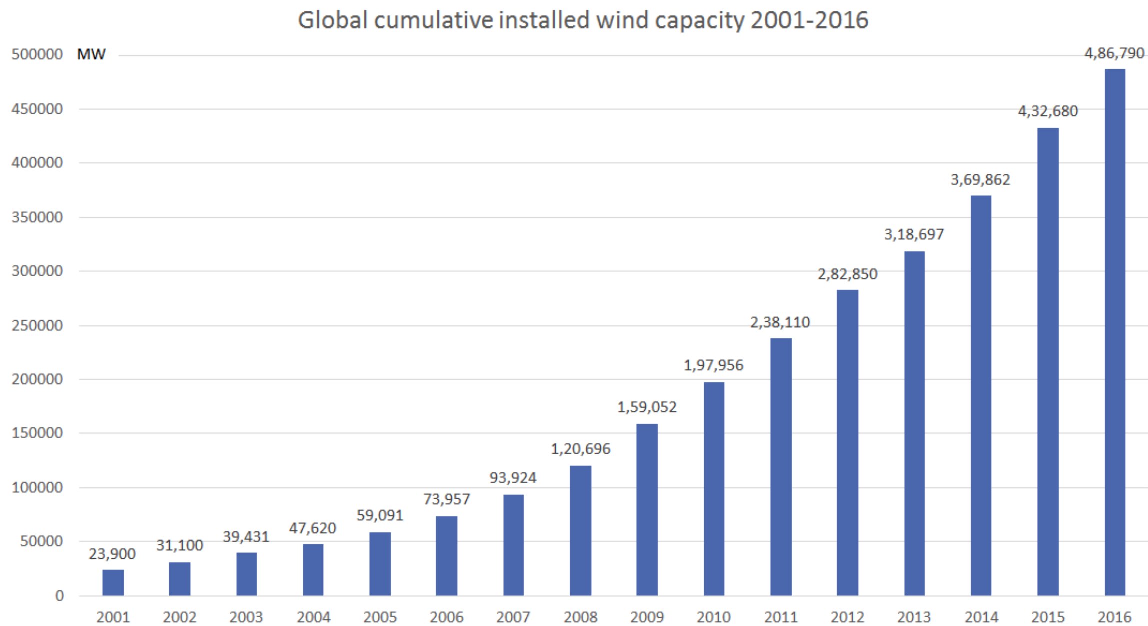

Figure 8: Global Cumulative Installed Wind Capacity [28]

Wind Turbine Types

There are two basic types of wind turbines which are the horizontal axis wind turbine (HAWT) and the vertical axis wind turbine (VAWT). This section will explain the differences, advantages, and disadvantages of the two types.

Horizontal Axis Wind Turbine

HAWT is the most commonly used type of wind turbine. It is closely related to windmills as the external shape consists of propeller-like blades that spin on a horizontal axis. HAWT has an electric generator and a rotor shaft facing the wind direction at the top of its tower. Small turbines that are used for small-scale power production generally use a wind vain to point the rotors in the wind direction, while larger ones have wind sensors that are connected to servo motors to direct the turbines. Also, larger turbines include a gearbox that is used to increase the rotation to speeds that are suitable enough for the electrical generator. However, according to the positioning of the rotors, air turbulence might occur behind the turbine. Hence, HAWT rotors are usually directed into a position upwind of their tower, made with qualities like high stiffness to prevent them from being pushed by high winds into the tower, and are placed at a considerable distance away from the tower. Despite turbulence, some downwind HAWT were built because they do not need a mechanism to keep them aligned with wind directions. Also, in downwind directions, high wind speeds can cause the blades to bend decreasing their swept area and, hence, their wind resistance [29]. Since the turbulence phenomenon occurs more often in downwind HAWT and causes fatigue failures that cannot be tolerated in such industries, upwind HAWT are always favored. Figure 9 shows a commercial HAWT installation.

Figure 9: Horizontal Axis Wind Turbine [31]

Advantages of HAWT:

1. Height of the tower gives access to stronger winds in wind shear areas. Statistics show that moving 10 meters higher in wind shear locations generally leads to an increase of 20% in wind speeds and 34% in power output.
2. As the direction of motion of rotors is always perpendicular to wind, the power is extracted during the full rotation. Hence, HAWT provides higher efficiencies than VAWT as VAWT needs backtracking against wind.

Disadvantages of HAWT:

1. Massive tower construction needed to support all the components.
2. Components need to be lifted to be placed in position.
3. HAWTs can be visible from large distances, which can disrupt the aesthetic view of landscape. Local opposition is sometimes noted.
4. Turbulence causes structural failure and fatigue.
5. Yaw control mechanism is needed to turn blades in wind direction.
6. Braking system is needed in cases of high winds to prevent the turbine from self-destruction.

Vertical Axis Wind Turbine

The main difference between HAWT and VAWT is the rotor blade design. VAWT has a rotor shaft that is placed vertically instead of horizontally. The advantage of this position is that there is no need to direct the rotor shaft towards the wind. It becomes very handy in locations where the wind is highly turbulent or variable. The VAWT tower does not need to support the various components as they can be placed on ground-level making maintenance a much easier job. The rotor shaft is usually placed on top of buildings or near the base because it is laborious to place the shaft on top of the tower. However, lower altitudes have lower wind speeds, so less energy is available for extraction. Also, when installed at lower heights, turbulence from objects nearby will occur. This causes vibrational problems like bearing wear and noise that lessens lifetime of material or demands higher maintenance costs [30]. When mounted on rooftops, VAWT becomes advantageous as winds are redirected to the top of buildings. Statistics prove that the optimal height to place a VAWT is at 50% of the building's height because wind speeds are at a maximum and turbulence is minimum. The following figures show 2 different types of VAWT.

Figure 10: Vertical Axis Wind Turbine [32]

Advantages of VAWT:

1. No yaw mechanism needed to turn rotor towards wind.
2. Easier maintenance because it can be located near ground.
3. Lower start-up wind speeds than HAWT.
4. Can be placed in locations without a tower.
5. Can take advantage of locations where wind accumulates like rooftops or hilltops.

Disadvantages of VAWT:

1. Lower efficiency than HAWT due to lower altitudes and backtracking.
2. VAWT blades cause an additional air drag.
3. They appear unfamiliar to anyone lacking expertise with the wind industry, which has caused scams over previous years.

Much like the previous couple of sections, this section will address fuel cells.

Fuel Cells

History

Despite the modern day technologies that surrounds them, the thought and application of fuel cells was present for more than 180 years. In the early 1800's, two British scientists, Anthony Charlisle and William Nicholson, explained the process of separating water into hydrogen and oxygen using electricity and named it electrolysis. In 1838, William Grove took this idea a step in reverse. He discovered that if two platinum electrodes were connected to a sealed hydrogen and oxygen tank at the end of the first and second electrode, and the other ends of the electrodes were immersed in sulfuric acid, a constant current was noticed to be flowing between the electrodes. He also noted that water levels started rising in the tubes with the ongoing process. Grove combined multiple sets into a series circuit and called it a gas battery, which later became known as a fuel cell. Although fuel cells were only a subject of curiosity in the 1800s, they became a theme of development and research in the 1900s [33]. The following table will highlight the major advancements and development of fuel cells throughout the years. What is important to note about this table is that after fuel cells were used in the automotive industry, there was a huge gap between 1993 and 2007 until they were thought of as backup power in stationary applications. After that, they commercial sales started in Japan and were carried on through the rest of the world. After the commercialization stage, fuel cell prices were 51$/kW in 2016.

Table 4: History and Development of Fuel Cells [33], [34]

Year	Development
1889	Scientists Langer and Mond modify Grove's invention and name it the fuel cell.
1950	General Electric invents Proton Exchange Membrane Fuel Cells (PEMFC).
1959	• 5 kW alkaline fuel cell demonstrated by Francis Bacon to power a welding machine.
	• Harry Ihrig demonstrated the first vehicle powered by a fuel cell. (20 horsepower tractor)
1960	NASA uses fuel cells in space missions.
1970	Oil Crisis forces the development of more renewable energy technologies including Phosphoric Acid Fuel Cells.
1993	First bus to be powered by a fuel cell.
2007	Fuel cells begin to commercially solidify as stationary backup power and auxiliary power inputs.
2008	Honda's FCX Clarity fuel cell is released.
2009	• Residential fuel cells are commercially available in Japan.
	• Thousands of fuel cell phone battery chargers are sold.
2010	• Cost of a fuel stack is 51$/kWh; 80% less than in 2002.
	• Sales quadrupled from 2008
2011	• Worldwide shipments grew by 214% from 2008.
	• World's first "trigeneration" fuel cell that produces heat, hydrogen, and electricity.
2013	Worldwide fuel cell capacity exceeds 200 MW due to the increase in stationary use.
2015	Toyota, Hyundai, and Honda companies commercial sales of fuel cell cars.
2016	• Including fuel cells in biological applications.
	• Cost becomes 52$/kW.

Basic Description

Fuel cells are electrochemical energy conversion devices that use the principle of reverse electrolysis to supply power from hydrogen-containing fuels. As long as enough fuel is supplied to the fuel cell, an electricity flow will always be present. To shed more light on the operation of a fuel cell, the main components need to be identified. These components are:

1. Two electrodes (Anode and Cathode)
2. Catalyst
3. Fuels (Hydrogen and Oxygen)

The following figure is a graphic display of the basic process that happens inside any type of fuel cell. Hydrogen fuel moves towards the anode to react with the platinum based catalyst to produce hydrogen positive ions (cations) and electrons. The cations move through the membrane that holds the catalyst to reach the cathode and react with oxygen atoms to give out water. On the other hand, the negative electrons need to pass through a circuit creating a flowing current and then rejoin the original Hydrogen atoms. Also, this process is exothermic, meaning that reaction gives out heat with the products.

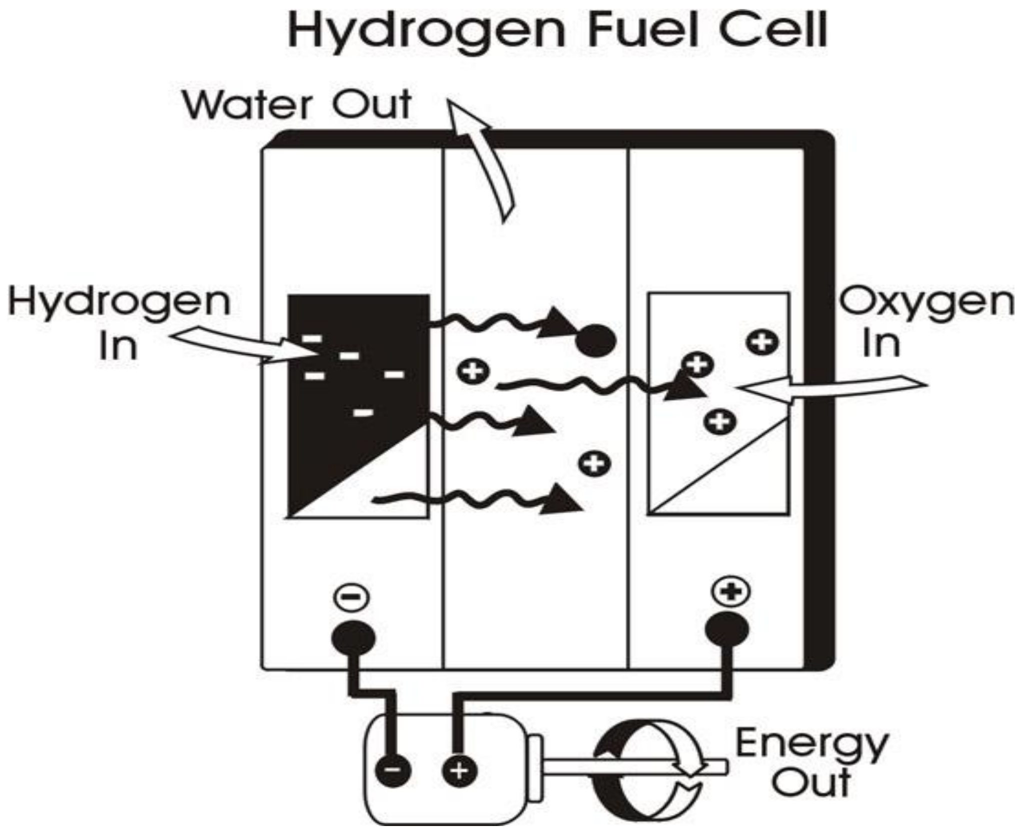

Figure 11: Hydrogen Fuel Cell Functioning [35]

Moreover, the power output from a single fuel cell is around 1 volt on average. Therefore, just like PV cells, they need to be formed together in fuel stacks to provide larger power outputs. A component that helps in combining these cells together is the bipolar plate. They are usually on the two opposite ends of a single fuel cell. While helping in putting a stack in formation, the bipolar plates also provide a hydrogen fuel distribution channel with their unique structure. As the fuel cell is exposed to oxygen penetration from the anode side as well, the bipolar plates prevent it by being shaped into accurate structures that can only allow the fuel to be accepted [37]. Fuel cells are commonly preferred as means of generating electricity for portable power generation because of their high conversion efficiency and other advantages mentioned above. While they are known as an efficient energy conversion device, fuel cells have important existing roles in energy storage applications. When used as a storage device, a fuel cell is combined with a fuel generation device, which is typically an electrolyzer or a reformer, to become known as a Regenerative Fuel Cell (RFC). Electrolyzers and reformers use different mechanisms to provide hydrogen fuel to the fuel cell system. The effectiveness of an RFC is due to the separation between generation and storage functions to optimize both.

The economic aspect is still being worked on to provide cheaper improvements to compete with current renewable technologies. That is why the benefits of these systems cannot be realized on the short term, which further pushes away short-term investors. Although some fuel cells have reached the commercial stage, technological leapfrogging is still needed to reduce the prices in others. Fuel cell systems stand to create great opportunities due to the fact that they connect two future energy carriers, which are hydrogen and electricity. The high conversion efficiency in fuel cells makes them the most appropriate for hydrogen electrochemical conversion. Figure 12 shows the distribution from 2002-2014 of fuel cell patents, and Figure 13 shows the shipments in MWs of stationary, transportation, and portable applications. Important notes are that U.S.A owns the most fuel cell patents, followed by Japan and Korea, and the worldwide stationary fuel cell capacity reached around 150 MW.

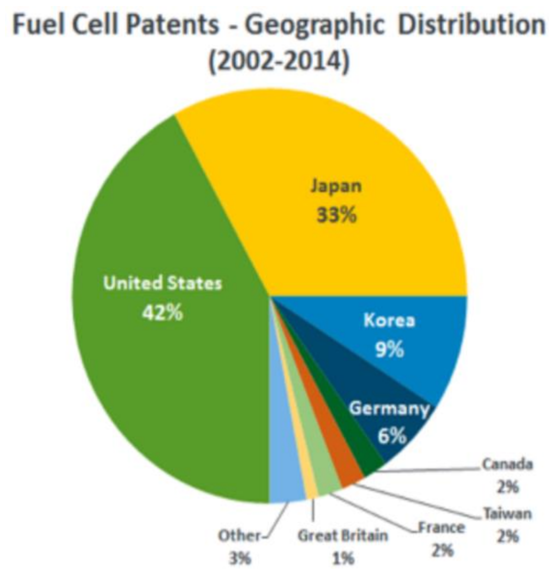

Figure 12: Fuel Cell Distribution in Countries [38]

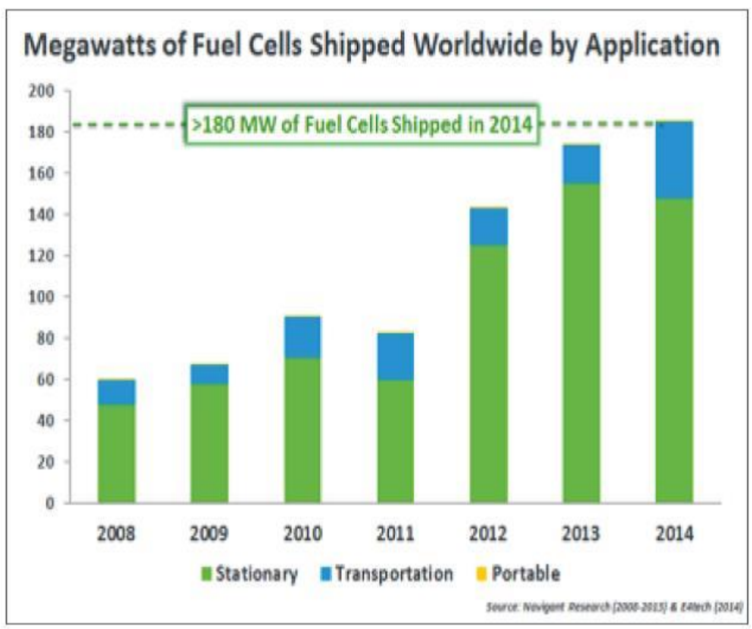

Figure 13: Fuel Cells Shipped in Application [38]

Fuel Cell Types

Fuel cells are categorized according to the electrolyte used inside them. The material of the electrolyte determines the type of chemical reaction that takes place, type of catalyst needed, fuel used, and operating temperature to produce electricity. Therefore, each fuel cell targets applications that are suitable with its components [38]. There are five main types of fuel cells, which are:

1. Proton Exchange Membrane Fuel Cells (PEMFC)
2. Solid Oxide Fuel Cells (SOFC)
3. Alkaline Fuel Cells (AFC)
4. Molten Carbonate Fuel Cells (MCFC)
5. Phosphoric Acid Fuel Cells (PAFC)

The following table lists the characteristics and application of these five types.

Table 5: Types and Characteristics of Fuel Cells [38], [39]

	PEMFC	SOFC	AFC	MCFC	PAFC
Electrolyte	Polymer Membrane	Ceramic (Stabilized Zirconia)	Liquid Pottasium Hydroxide (KOH)	Molten Carbonate	Liquid Phosphoric Acid
Catalyst	Platinum	Perovskites	Platinum	Nickel	Platinum
Operating Temperature ($°C$)	50-100	600-1000	90-100	600-700	150-200
Charge Carrier	H^+	O^{-2}	OH^-	${CO_3}^{-2}$	H^+
Cell Components	Carbon Based	Ceramic Based	Carbon Based	Stainless Steel	Carbon Based
Fuel	Methanol, H_2	H_2, CH_4, CO	H_2	H_2, CH_4	H_2
Electrical Efficiency (%)	25-35 (Stationary)	35-43	60	45	>40

Combined Power and Heat Efficiency (%)	70-90	<90	>80	>80	>85
Power Range (kW)	<1,000	10-100,000	1-100	100-100,000	50-1,000
Power Density (mW/cm^2)	300-1,000	250-350	150-400	100-300	150-300
CO Tolerance	Poison	Fuel	Poison	Fuel	Poison
Balance of Plant	Low-Moderate	Moderate	Moderate	Complex	Moderate
Advantages	Solid electrolyte. Fast start-up. Low Temp.	Solid electrolyte. High efficiency. Flexible fuel & catalyst.	Higher performance due to alkaline electrolyte. Flexible catalyst.	High efficiency. Fuel & catalyst flexibility.	Tolerance to impurities of hydrogen.
Application	Backup & portable power. Vehicles. Small distribution.	Utilities. Auxiliary input. Large distribution.	Space. Military.	Utilities. Large distribution.	Distributed generation.

Energy Storage Systems

As implied by their name, energy storage systems store energy for times when energy can be of more important use. The devices that store energy are usually called accumulators, and the process of storing energy varies depending on the demand of energy. Some of the most common energy storing technologies includes (i) Fossil Fuel Storage (FFS); storage of fossil fuels is the most economically dominant method used to keep balance between the average yearly consumption and primary production of energy, (ii) Pumped Hydroelectric Storage (PHS); depends on pumping water from reservoirs of low altitude to reservoirs of higher altitudes to yield higher gravitational potential energy, (iii) Thermal Energy Storage (TES); manipulation of sensible or latent heat properties of different substances, (iv) Compressed Air Energy Storage (CAES); storing compressed air in reservoirs that are mostly located underground, (v) Electrochemical Energy Storage (EES); includes storing energy using the chemical properties of different elements, (vi) Flywheels Energy Storage (FES); rotational energy by accelerating and decelerating rotors to high speeds [40]. However, since the focus in this thesis is to reduce the use of non-renewables as much as possible, using fossil fuel storage will not be considered. Also, systems such as CAES, TES, and PHS are better used in large-scale applications as the cost per unit energy produced becomes significantly higher when used in residential or small-scale applications, producing overall lower energy utilization cost efficiency. For example, TES and FFS both depend on the use of conventional systems that burn fossil fuels using heat engines and solar electric technologies. Moreover, CAES can only be used as a secondary system to gas power plants in order to decrease the quantities of natural gas burnt whilst decreasing the greenhouse emissions simultaneously [41]. Unlike CAES, PHS is more flexible as a storage system since it can be combined with any other energy generating technology given the appropriate site to build or place the compulsory infrastructure. However, PHS is still considered more energy efficient when used in macro-grids, and for hydro systems, a delay time of at least four minutes should be taken into account. Overall energy efficiency and the least delay time are the main aspects looked upon in an energy storage system [42]. Therefore, EES and Flywheels are the most appropriate candidates for the study made in this paper. The EES category includes different types of batteries, super capacitors, and fuel cells. According to literature, flywheels are not as efficient as batteries or super capacitors when used in REMGs, and fuel cells are showing higher hopes in becoming cheaper and more environmentally friendly than both batteries and super capacitors. Therefore, the main type of ESS that will be used throughout this thesis and in the case study will be fuel cells [42].

Various studies have been taken to utilize ESS in order to improve the amount and quality of renewable energy in electric grids. As an example, Kaldellis et al. studied the applicability of ESS technologies on small islands according to type and size of the ESS [43]. The approach was to estimate the annual energy peak demand by taking monthly averages for the whole year in order to calculate the minimum LCOE needed for each specific island and for a range of different ESS as well. However, the main source of energy in that study was solar energy and the storage system only accounted for the PV system.

Carbajales Dale et al. discussed the level of compatibility of renewable energy sources with storage systems [44]. Compatibility was measured by taking inputs such as Depth of

Discharge (DOD), which defines the highest levels of discharge from the ESS, and the capacity factor of different technologies. In that study, storage systems were divided into either geological storage that includes CAES and PHS, or all types of batteries. In the results and discussion part, it was clearly shown that the better ESS for their study was the geological storage system as the numbers indicate that they were economically and technically more feasible than batteries.

In addition, Denholm and Hand executed a study that specifically concentrated on the numerical analysis of the penetration of RES when a storage system is used alongside [45]. The authors state that adding an ESS to mass generation systems on large grids can act as a successful substitute to retrieving the base load from conventional non-renewable sources such as fossil fuel burning.

In further studies, authors Harris et al. tackle scenarios to have higher renewable energy penetration from ESS in the United States [46]. They mention that the optimization of the sizing of ESS is highly dependent on the time frame and quantity of demand. Many other studies emphasize the importance of ESS for the future of RES. Furthermore, unlike the previous examples, some resources suggest that the availability of certain types of ESS can play a huge role in determining the feasibility in geographical areas [46]. In any case, more studies should be made on the use of different types of RES with ESS, while taking into consideration the energy mixture that includes the instability of renewable sources. It is safe to state that implementing ESS to renewable systems will definitely increase the fraction of RES and decrease any excess or dumped energy. With integrated large-scale systems, the amount of dumped energy would be even higher without ESS. In order to move forward towards greener technologies with higher renewable fractions, a better understanding must be available on the functionality and feasibility of energy storage systems.

Hybrid Systems

Recent studies that will be mentioned in this section have shown that implementing REMGs can be feasible whether they are for isolated communities, partial demand, or entire demand obligations. The aim of all these studies, in terms of feasibility, is to examine aspects like Levelized Cost of Electricity (LCOE) and the fraction of electricity contribution of the RES. These metrics are evaluators of the overall performance of the system. However, evaluating an energy system of this sort is not as effortless as it might seem. The reason is that the RES is composed of different technologies and components, which can be optimum on their own, but not as a single system. Also, the availability of the components is according to regional preference, and determining the size of them is another challenge to reach the optimal outcome. Therefore, a software called "Hybrid Optimization Model for Electric Renewables" (HOMER) was used in some of the studies as a solution to the challenges mentioned. HOMER is a globally recognized software that is used in more than 193 countries with more than 150,000 users. The objective of this software is to optimize the evaluation of any micro-grid that is entered by the user, and it is done by a comparison of LCOE, NPV, and the fraction of RES. Mistakes that have been made before by choosing the correct renewable energy with the incorrect sizing, or vice versa, can be eliminated using HOMER [47].

Examples of articles that use this software include a study made in an Ethiopian rural area by Bekele and Palm [48]. The REMG was based on solar and wind energy with resources that were accumulated using satellite data and forecasting models, which were inputs to HOMER software. Analyzing and comparing the RES fraction and LCOE of the two best solutions determined economic feasibility. The first option showed 0.383 $/kWh with 51% RES fraction, while the second option showed 0.464 $/kWh with 81% RES fraction.

Bekele made a further study with Tadesse for another region in Ethiopia, but this study included more renewable energy sources along with the solar and wind such as diesel generators, hydropower, and batteries [49]. The residual of the numerous solutions that were offered by HOMER ranged between 70% to a 100% for RES fraction and 0.10 to 0.16 $/kWh for LCOE. Among those solutions, it was agreed upon by the authors that the best solution was an LCOE of 0.108 $/kWh and a RES fraction of 95% to give a combination of lowest LCOE with maximum fraction.

Moreover, Mohammed et al. worked on the analysis of a standalone PV and fuel cell hybrid system for a whole city named Brest in France [50]. The weather data and load demand for the city were inputs to HOMER software along with the capital, replacement, and operation and maintenance costs of the components. It turned out that the proposed system is feasible with an electrical energy production of 8.513 GWh/year and energy consumption of 8.207 GWh/year, with the cost of electricity becoming 0.12 $/kWh. As this study was made for an entire city, environmental pollutants, specifically carbon dioxide and nitrogen oxides, were shown to decrease by a total of nearly 10 tons/year.

In another study in Bozcaada Island, Turkey, Kalinci et al. compared two energy production systems that were assumed to provide electricity for the assigned location [51]. The first method was a hybrid wind energy system and the second one was a hybrid solar, wind, and fuel cell system. It showed that the LCOE and NPV calculated using HOMER was less than the wind energy hybrid system. For the hybrid wind energy system, the LCOE and NPV were 1.016$/kWh and $14.6 million, respectively. For the hybrid solar,wind, and fuel cell system, the LCOE and NPV were 0.93$/kWh and $11.9 million, respectively.

Similarly, Khan and Iqbal studied the economic feasibility of different combinations of hybrid systems for a domestic household in Newfoundland, Canada [52]. The energy generation methods that were to be examined were solar, wind, hydro, diesel generator, batteries, and fuel cells. With more than 40,000 combinations taken into account, the optimal one was diesel, wind, and battery system with an LCOE of 0.497$/kWh. However, that conclusion was only made due to the high pricing of fuel cells and their components. It was stated that if the fuel cell prices were to decrease by 65%, the optimal option would be diesel, wind, fuel cell, and battery system. It was also stated that if the prices decrease by a further 15%, the most economically feasible option would a wind and fuel cell hybrid system with the LCOE dropping even further to 0.427$/kWh.

Furthermore, an economic analysis was made for different combinations of hybrids in Peninsular, Malaysia [53]. In Peninsular, 19% of the total annual energy production is transferred to homes that completely depend on the grid for energy. The main purpose of the study was to examine the viability of two scenarios using HOMER software to provide power to households. Scenario A is a hybrid combination of a thermal management system and fuel cell system. Scenario B is exactly the same as scenario B but with a battery storage system as well. For a lifetime of 20 years, the most cost effective scenario turned out to be scenario B. The difference in investment costs is $90, with scenario A and B being $920 and $830, respectively. However, the option of not building any RES and depending on the grid for electricity is economically more stable. The authors also add that the reason scenario B is more cost effective is because the fuel cells are being used less than scenario A. Hence, the operation and maintenance costs become much less for scenario B. Also, since fuel cells undergo exothermic reactions, heat removal should be deeply considered when joining them in hybrid systems. That is why scientists and researchers are trying to find ways in which the excess heat from fuel cells can be rechanneled to be more useful (e.g. water heating in households).

Another study initiated by Lonchar was about a hybrid system consisting only of a fuel cell system and solar panels with economic analysis using HOMER in Arizona, United States of America [54]. Similar to the previous examples, this study also aims to supply energy to a regular household. Alterations in the sizing of each of the components of the hybrid system with the change in price each time were noted down. The lowest LCOE was 0.044$/kWh, but this project was for a lifetime of 30 years. What was very useful throughout the study was the analysis on the important changes in pricing, and there three major points that were noteworthy. First, unit cost is a major contributor to the size of the system because the bigger the system, the costlier it will be. Second, the components are always sized to handle the toughest and most extreme working conditions for a larger factor of safety. Third, the size of the system is directly proportional to the efficiency of its components.

As for projects for households, Vokas et al. investigated a comparison between a regular solar farm and a solar/thermal hybrid system for heating and cooling demands of houses in the region of Athens and how the geographical factor can affect the choice of using a hybrid system [60]. The study concludes that for an area of 30 m^2, the thermal efficiency of a hybrid solar/thermal hybrid system is 9% lower than conventional solar collector. Alone, the solar system can cover 31.9% of the cooling load and 54.3% of the heating load. The hybrid system has 6.6% less efficiency. However, the solar/thermal combination has a payback period of 4.6 years, which makes it a viable choice for this example. Also, the authors state that research promises high efficiencies in such hybrid systems and can help in determining the feasibility of these systems.

For feasibility calculations, a study made by Sinha and Chandel discussed 19 different software that can be used to calculate the economic aspect of hybrid system studies [62]. It indicates that HOMER Software is one of the software that can be depended upon to simulate this type of system analysis. Authors further imply that this software has an advantage of flexibility for users to further simulate hybrid system applications. Furthermore, the next section provides insight on what has been done in METU NCC until 2017 that is related to this thesis.

METU NCC Projects

Middle East Technical University, Northern Cyprus Campus (METU NCC) is considered an isolated society that is located on top of a hillside in a rural area in the northern part of Cyprus. Due to the distinctive positioning and self-containment of the university, it is an institution with great potential in terms of renewable energy and REMG testing, and it is especially unique for its solar capabilities. Four studies exist in previous literature regarding the feasibility of an REMG system in METU NCC, and they each add incremental contributions to the overall progress in renewables on campus.

In 2011, Pathirana and Muhtaroglu worked on the feasibility of installing a PV plant in METU NCC [55]. The study was made using different PV technologies, and it was based on monthly averages of demand and Global Horizontal Insolation for the year 2011. The authors noted that months February and August reported the lowest and highest monthly average demand, respectively. In order to meet the monthly average demand for the whole year, the highest monthly average was considered, and the PV system was designed to produce around 6 MW. The two best options that were discussed by the authors to deal with the surplus energy were either to sell the excess energy back to the grid or store it within batteries. LCOE with an energy storage system turned out to be 0.24$/kWh, while LCOE without the batteries was almost half the price at 0.14$/kWh.

In another research, Tariq studied ways to deal with the sizing of grid-connected REMGs and developed a unidirectional metering method [56]. METU NCC was the case study of the research, and Tariq used data such as Theoretical Metrological Data (TMY) values that are generated by Meteonorm [57]. Demand and solar data were extracted from TMY values and were used through the period between June 2013 and May 2014. In the discussion and results part, the author states that sizing of the PV system relies on intention. In other words, if the objective of the user were to maximize economic benefit, the size would be 1.8 MW. However, as there is no analysis for an energy storage system, any surplus energy is considered waste energy. Therefore, another objective might be to reduce the excess energy generated. If that were the case, the size of the system becomes 600 kW. The lowest reported LCOE in this study was 0.13$/kWh.

For the third study, Yenen examined the feasibility of a solar/wind hybrid system in METU NCC [58]. Very similar to the second study, solar and wind data collection was based on the TMY values, and the time period of this study was also from June 2013 to May 2014. Yenen investigated a 1.3 MW PV plant that was located around 10 km away from METU NCC and developed a model of PV plant for the campus. The difference in annual energy generation between the actual plant and the hypothetical one was only 4%. For wind energy generation, the author studied what was available in TMY values for the same 11 months. According to Yenen's results, it would not be feasible to install any wind turbine with a capacity less than 2 MW. Yenen made calculations for the capacity factors, which vary according to the hub height of the wind turbine. As a result, the maximum capacity factor that was reached was 11.44% at a hub height of 47 m.

Sadati et al. made the fourth study in which the feasibility of an REMG that consists of a PV power plant, a choice of batteries, and pumped hydropower [59]. Authors argue that at the current state of renewable energy costs, it would be economically inefficient to create a standalone REMG on METU NCC grounds. Results of the study highlight that a mixture of all the technologies is also not efficient. The best option is a PV/PHS system with an 85% RES fraction. However, challenges were noted in pumping water due to the difficult geographical factor. The next best option is having a 30% RES fraction for a PV/Battery system.

In short, literature investigated the feasibility of RESs and REMGs throughout different locations that have unique climate characteristics. Studies have shown variable ways to tackle the selection and sizing of the technologies that are taken into account in an REMG. However, more studies need to be directed towards the sensitivity of mixing different technologies together. The availability of technologies in certain places can be a major concern even if the theoretical energy production is suitable. Furthermore, as much as fuel cells are thriving in renewables for the past decade, studies made in METU NCC still do not consider any of the multiple types of fuel cells in REMGs.

Chapter 3 - Methodology

In this chapter, the equations that are necessary to extract the power output of solar panels, wind turbines, and fuel cell systems will be clearly stated along with any assumptions that need to be taken into account. Also, the optimal type of grid connection between the system and the outside world and the type of current within the system will be discussed. Finally, the levelized cost of electricity and net present cost calculations will be clarified.

Power Output of Solar Panels

The hourly power output from the solar panels is given by the following Equation (1) [65].

$$P = A\eta_{PV} I_{PV} P_f \tag{1}$$

Where;

$$P = Electrical\ power\ produced\ (kW)$$

$$A = Area\ of\ module\ (m^2)$$

$$\eta_{PV} = PV\ module\ efficiency\ (\%)$$

$$I_{PV} = PV\ panel\ total\ hourly\ insolation\ (^{kW}/_{m^2})$$

$$P_f = Total\ losses\ in\ system\ due\ to\ shade, dust, etc..(\%)$$

PV panels have a set of characteristics given to them by PV manufacturers, and these include:

1. $T_{ref} = Panel\ reference\ temperature$
2. $\eta_{ref} = Nominal\ efficiency$
3. $NOCT = Nominal\ operating\ cell\ temperature$
4. $I_{NOCT} = Reference\ hourly\ insolation\ for\ NOCT$
5. $\beta_{ref} = Temperature\ coefficient\ of\ panel(°C)$

Using the variables given above with enough information about the ambient temperature T_A, Equation (2) for the module efficiency η_{PV} can be deduced [65], which varies with changes in panel insolation and temperature.

$$\eta_{PV} = \eta_{ref}\{1 - \beta_{ref}\left[T_A - T_{ref} + (NCOT - T_A)\frac{I_{PV}}{I_{NOCT}}\right]\} \quad (2)$$

Power Output of Wind Turbines

Manufacturers, in accordance with variable experimental tests and measurements, calculate wind turbine characteristics. The most important characteristic is the power output from wind energy through the rotors. When manufacturers plot the power output against wind speeds, all losses and parameters are taken into account in the graph. Therefore, a module of the wind turbine can be assumed by simply looking at the power vs wind speed graph. To calculate the mechanical power output at any given time, the Equation (3) is used [66].

$$P(t) = 0.5C_p\rho AV(t)^3 \tag{3}$$

Where;

$$P(t) = Mechanical\ power\ output\ at\ time\ t$$

$$C_p = Power\ coefficient$$

$$\rho = Density\ of\ Air$$

$$A = Swept\ area\ of\ rotor$$

$$V(t) = Wind\ speed\ at\ time\ t$$

The power coefficient is expressed as the ratio between the rotor tip-speed and wind speed. The maximum theoretical power coefficient is recorded to be no more than 0.59, and Equation (4) is used to show the Tip-Speed Ratio (TSR).

$$TSR = {}^{\omega R}/_{V} \tag{4}$$

Where;

$$\omega = Turbine\ angular\ speed$$

$$R = Turbine\ radius$$

Since wind speed is usually measured at a certain position, wind speeds at higher or lower locations can be predicted using the power exponent (α) in Equation (5).

$$V_{hub} = V_{act} * (\frac{Z_{hub}}{Z_{act}})^{\alpha} \tag{5}$$

Where;

$$V_{hub} = Wind\ speed\ at\ hub\ height\ (\frac{m}{s})$$

$$V_{act} = Wind\ speed\ at\ anonemeter\ (\frac{m}{s})$$

$$Z_{hub} = Hub\ height\ (m)$$

Every wind turbine comes with a sheet from the manufacturers that give essential parameters for the user, and these parameters include [66]:

1. Rated Power; Maximum capacity of wind turbine.
2. Hub Height; Height of turbine from ground level.
3. Cut-in Wind Speed; Minimum wind speed to generate electricity.
4. Cut-out Wind speed; Wind speed at which turbines are rested to avoid damage.
5. Rated Wind speed; Wind speed at which the turbine generates rated power.
6. Survival Wind Speed; Maximum wind speed a turbine can withstand without damage.

Power Output of Fuel Cells

As mentioned before, a simple fuel cell consists of an anode and a cathode that undergo two half reaction processes. The first half reaction process happens at the anode where hydrogen atoms that are supplied by hydrogen tanks decompose into hydrogen ions and electrons. The second half reaction happens at the cathode where protons (hydrogen ions) travel through a membrane and combine with oxygen to produce water and energy, and is shown in the following chemical reactions.

$$H_2 \rightarrow 2H^+ + 2e^-$$

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O$$

The performance of a fuel cell system depends on the interdependence of voltage and current. A graph, called the current voltage curve, represents this mutuality. Hence, the output voltage can be a function of current, and if the area of fuel cell is known, current density can be calculated. Ideally, a fuel cell can supply infinite current as long as the voltage is maintained constant. However, in reality, actual voltage output is much less than reversible theoretical voltage, and the more the cell draws current, the less voltage will be supplied. The reason behind this decrease in voltage is the fuel cell losses that accompany the process, and they are categorized as follows [67]:

1. Concentration losses that are due to mass transport.
2. Activation losses that happen during electrochemical reactions.
3. Ohmic losses that are due to electronic and ionic conduction.

The following calculations are retrieved from [67]. The actual output voltage is simply the reversible output voltage without the total of the losses and can be seen in Equation (6).

$$V_{act} = V_{rev} - \eta_{con} - \eta_{act} - \eta_{ohm} \tag{6}$$

Where;

$$V_{act} = Actual\ voltage\ output\ (V)$$

$$V_{rev} = Theoretical\ voltage\ output\ (V)$$

$$\eta_{con} = Concentration\ losses$$

$$\eta_{act} = Activation\ losses$$

$$\eta_{ohm} = Ohmic\ losses$$

Moreover, the power of a fuel cell is determined by Equation (7).

$$P = iV \tag{7}$$

Where;

$$P = Power\ (W)$$

$$i = Current\ density\ \left({}^{A}/_{cm^2}\right)$$

$$V = V_{act}\ (V)$$

A more efficient characteristic than power is the power density curve, which is a representation of power density against current density of a fuel cell. Fuel cells are designed to function at or below maximum power densities because of 2 reasons. The first reason is if current densities are above maximum power densities, power density and voltage efficiency drop. The second reason is if current densities operate below maximum power densities, only power density will decrease while voltage efficiency increases. Figure 14 shows a visual explanation of the relationship. Note that ideal fuel cell voltage can never be reached due to activation, ohmic, and mass transport losses. Also, there is an indirectly proportional relationship between voltage and power density.

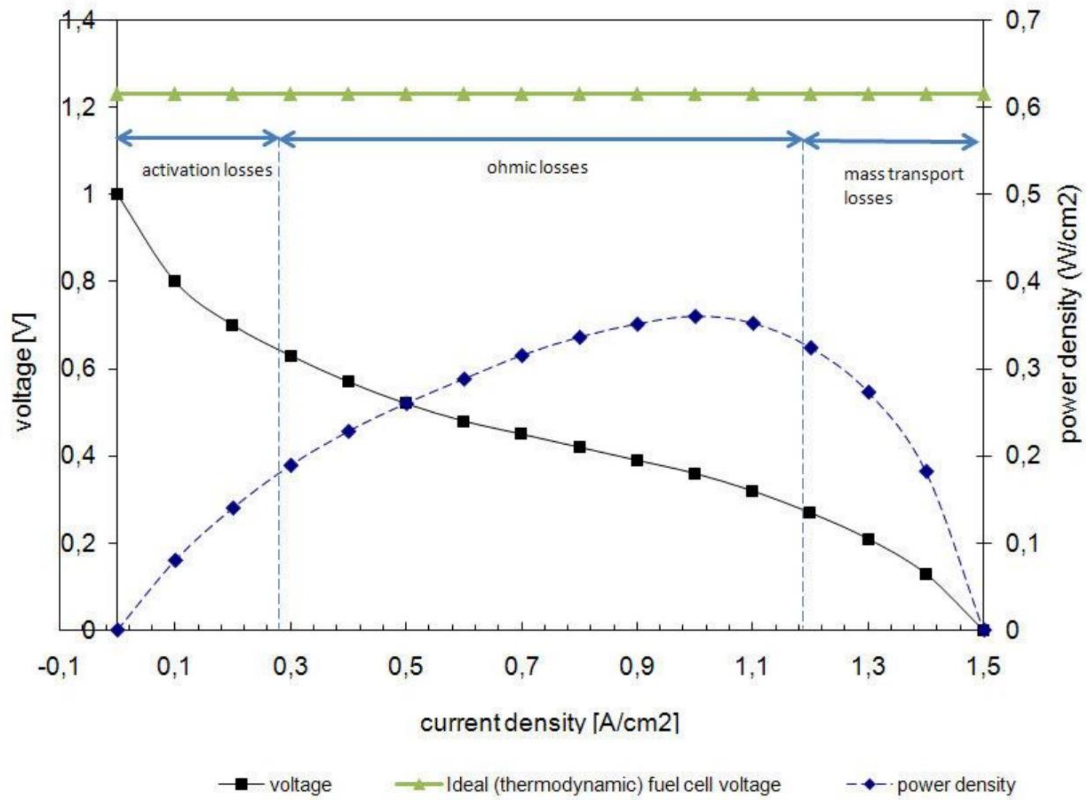

Figure 14: Voltage, Current Density, and Power Relationship in Fuel Cells

The reversible theoretical voltage can be calculated by Equation (8).

$$V_{rev} = \frac{\Delta g}{nF} \tag{8}$$

Where;

$$\Delta g = Free\ energy\ change\ in\ reaction\ (^{KJ}/_{mol})$$

$$n = Number\ of\ electron\ moles\ transferred\ (moles)$$

$$F = Faraday's\ Constant\ (Farad)$$

This theoretical voltage is highly dependent on pressure, temperature, and catalysts within the fuel cell. The relationships between voltage and temperature and voltage and pressure are shown in Equations (9) and (10), respectively.

$\frac{dV}{dT} = \frac{\Delta s}{nF}$ (9)

Where $\Delta s = Entropy\ change\ ({}^{KJ}/_{mol})$

Entropy change for all fuel cells is negative, showing that theoretical output voltage decreases with increase in temperature.

$\frac{dV}{dp} = -\frac{\Delta v}{nF}$ (10)

Where $\Delta v = \ Volume\ change\ (cm^3)$

The variation of theoretical output voltage with pressure is connected with change in volume of reaction. If volume change is negative, voltage will increase which, in turn, increases pressure. However, temperature and pressure have minimal effects on theoretical voltage. On the other hand, chemical activity severely affects output voltage and can be explained with the Nernst equation (11).

$V_{act} = V_{rev} + \frac{R_u T}{nF} \ln\left(\frac{P_{H_2} + (P_{O_2})^{\frac{1}{2}}}{P_{H_2O}}\right)$ (11)

Where;

$$R_u = Universal\ Gas\ Constant\ \left({}^{J}/_{K\ mol}\right)$$

$$T = Temperature\ (K)$$

$$P_{H_2} = Partial\ pressure\ of\ Hydrogen\ \ (Pa)$$

$$P_{O_2} = Partial\ pressure\ of\ Oxygen\ (Pa)$$

$$P_{H_2O} = Partial\ pressure\ of\ Water\ (Pa)$$

The theoretical fuel cell efficiency is given by equation (12).

$\varepsilon_{rev} = \frac{\Delta G}{\Delta H}$ (12)

Where;

$$\Delta G = Change\ in\ Gibb's\ free\ energy$$

$$\Delta H = Change\ in\ enthalpy\ ({}^{kJ}/_{kg})$$

The maximum theoretical efficiency is almost 83%. Any measured actual efficiency should be lower than the theoretical efficiency due to differences in theoretical and actual voltages. The 2 major losses are fuel utilization losses and voltage losses. So, to calculate actual efficiency (ε_{act}), fuel utilization losses (ε_{fuel}) and voltage losses (ε_{volt}) need to be subtracted from ε_{rev}. Equations (13), (14), and (15) show the calculations for ε_{act}, ε_{fuel}, and ε_{volt}.

$$\varepsilon_{act} = \varepsilon_{rev} - \varepsilon_{fuel} - \varepsilon_{volt} \tag{13}$$

$$\varepsilon_{fuel} = \frac{{}^{i}/_{nF}}{v_{fuel}} \tag{14}$$

$$\varepsilon_{volt} = \frac{V_{act}}{V_{rev}} \tag{15}$$

Where;

$$i = Current\ generated\ in\ fuel\ cell\ (A)$$

$$v_{fuel} = Rate\ of\ fuel\ supplied\ to\ cell\ \left({}^{mol}/_{S}\right)$$

It is very important to know if the hybrid system is connected to the grid or not because it has a great impact on the LCOE and NPV of the system. Therefore, the next section discusses what happens when the hybrid system is connected to the grid or not.

Grid Connection

An important notion to understand is how, or if, the hybrid system is connected to the grid. There are three ways in which such systems can be defined on an electricity grid.

First, there is the choice of being connected to the grid all the time, which is ordinarily called Grid-Tied or Grid-Connected. The advantage of this type, as implied by the name, is that the user's system is always connected to the grid and any electricity produced will be fed to it. For example, if the system depends on solar power and the low sun intensity was unplanned for, the user can still have the grid as backup. An advantage of this type of connection is that battery banks or other forms of storage devices are not needed. That, in turn, will decrease the overall cost of the system. However, not having a place to store energy is a drawback if the grid is down and demand is not met. The user can also take advantage of net metering, which means any extra electricity produced by the hybrid system can be sold back to the grid. Nevertheless, utility companies usually charge users with monthly fees.

Second, there is the choice of being off the electricity grid is called Off-Grid or Standalone systems. Users who know their hybrid system is efficient enough without the grid, also have a grid of which the electricity is unreliable, or who live in remote places that do not have a grid, usually embrace this type of connection. The advantages are that the user would not have to deal with grid failures if a grid is present, and the feeling of self-sufficiency. However, to be self-sufficient in terms of electricity, this connection is the most expensive one due to the necessity of buying a battery bank. Since there are more components in this type of grid connection, operation and maintenance costs, along with replacement costs for batteries, act as a crucial economic factor. In some extreme cases, another source of conventional power production might be needed to meet the energy demand.

The third option is the Hybrid system, which is considered to be the best of both worlds. This system is connected to the grid using a switch that is usually automatic and disconnected from the grid using that same switch. Switching whenever needed to the grid is a major advantage, especially in times when the user knows that the demand is larger than the capacity of the system. Knowing that the grid is available also means that downsizing the storage will save space and money without compromising the output. The hybrid system is less expensive than the standalone because it needs less maintenance. The only disadvantage is that this system cannot be implemented in remote areas with no grid.

System Performance

The performance of the system depends on the RES fraction contributing to green energy and the Capacity Factor of the entire system. Equations (16) and (17) give a clear idea about how these two variables are calculated.

$$RES\ Fraction = \frac{Annual\ Energy\ Generated\ by\ RES}{Annual\ Demand} \tag{16}$$

$$CF = \frac{Annual\ Energy\ Generated\ by\ RES}{Installed\ Capacity * Time} \tag{17}$$

RES Fraction and CF calculations are crucial when it comes to the sizing of components of the entire system because they help in choosing the best possible option out of multiple calculated system options.

Economic Modelling

The economic aspect of the system is basically assessed by two calculations; The Levelized Cost of Electricity (LCOE) and the Net Present Value (NPV). Equation (18) shows how the LCOE can be calculated [62].

$$LCOE = \frac{Sum\ of\ Cycle\ Cost}{Lifetime\ Power\ Produced} = \frac{I + \sum_{t-1}^{n} \frac{M+F}{(1+r)^t}}{\sum_{t-1}^{n} \frac{E}{(1+r)^t}} \tag{18}$$

Where;

$$I = Initial\ Investment\ (\$)$$

$$M = Annual\ Maintanence\ Cost\ (\$)$$

$$F = Annual\ Fuel\ Cost\ (\$)$$

$$E = Annual\ Energy\ Produced\ (kW)$$

$$r = Annual\ Discount\ Rate\ (\%)$$

$$n = Lifetime\ of\ System\ (Years)$$

There are some important notes regarding the previous equation that need to be addressed:

1. Annual maintenance is assumed to be around 1.5% of initial cost for every component.
2. Fuel cost is not considered for the system that is going to be tested.

3. Total cost includes the electricity bought from the grid in the case of Grid-Tied connection.

Moreover, Equation (19) represents the method of calculating NPC.

$$NPC = \sum_{t=0}^{n} \frac{C}{(1+r)^n} \tag{19}$$

Where;

$$C = Cash\ Flow\ Over\ Lifetime\ (\$)$$

$$r = interest\ rate\ (\%)$$

$$n = lifetime\ of\ project\ (years)$$

NPC accounts for initial, operation and maintenance, and replacement costs through a discount factor included in C. The values for n, r, and the inflation rate are considered to be 25 years, 9%, and 6% respectively [63]. NPC has an advantage over LCOE because it does not directly include energy generation by the system. Therefore, it can be considered a better representative when it comes to pure economic feasibility. LCOE directly depends on electricity generation and whether or not excess electricity is included in the calculation. This can massively affect the results for the tested system. The salvage value, or the cost of a component after its lifetime is over, is also considered in NPC. Salvage values for all components are calculated based on a relation between remaining lifetime and depreciation.

Environmental Analysis

As Carbon Dioxide is the main greenhouse gas that is emitted by regular means of energy generation, it will be the only greenhouse gas that will be considered from an environmental aspect with a penalty cost of 50 $/ton [74]. Renewable energy sources are considered to have no greenhouse emissions throughout this paper. The electrolyzer in the fuel cell system is the only component in the hybrid system that can produce carbon dioxide. However, the yearly amount is negligible. The yearly amount of avoided carbon dioxide A_{CO_2} and penalty for producing carbon dioxide P_{CO_2} are simply:

$$A_{CO_2} = R_{CO_2} * E_{RES} \tag{20}$$

$$P_{CO_2} = E_{CO_2} * C_{CO_2}$$

Where;

$$R_{CO_2} = Amount\ of\ Carbon\ Dioxide\ generated\ (\frac{kg}{kWh})$$

$$E_{RES} = Renewable\ Energy\ Production\ (kWh)$$

$$E_{CO_2} = Yearly\ Emissions\ of\ Carbon\ Dioxide\ \left(\frac{kg}{year}\right)$$

$$C_{CO_2} = Penalty\ of\ Carbon\ Dioxide\ production\ \left(\frac{\$}{kg}\right)(Country\ Based)$$

HOMER Software Validation

Before analyzing the case study, a test will be made to make sure that HOMER Software uses identical or near-to identical equations to analyze any case study inserted by a user. This test will include a solar panel/wind turbine hybrid system with an AC/DC converter that are connected to a grid. The LCOE and NPC calculations are done by the software by picking out a number of hybrid system results by the process of optimization. Table 6 shows the inputs that will be given to HOMER Software. After that, hand calculations using equations (1-20) should prove the credibility of this software.

Table 6: Inputs for HOMER Verification

INPUTS	
RESIDENTIAL ELECTRIC LOAD	
$Average\ (\frac{kWh}{day})$	11.26
$Average\ (kW)$	0.47
$Peak\ (kW)$	2.09
$Load\ Factor\ (\%)$	0.22
SIMPLE RATE GRID	
$Grid\ Power\ Price\ (\frac{\$}{kWh})$	0.150
$Greenhouse\ Emissions\ (\frac{g}{kWh})$	636.08
FLAT PLATE SOLAR PANEL (DC)	
$Capacity\ (kW)$	4.0
$Capital\ (\frac{\$}{kW})$	1,800
$Replacement\ (\$)$	1,500
$Operation\ \&\ Maintenance\ (\frac{\$}{year})$	10
$Nominal\ Operating\ Temperature\ (°C)$	47
$Nominal\ Efficiency\ (\%)$	16
$Temperature\ Effects\ (\frac{\%}{°C})$	-0.50

$Derating\ Factor$ (%)	80
$Lifetime\ (years)$	25
WIND TURBINE (AC)	
$Capacity\ (kW)$	10.0
$Capital\ (\frac{\$}{kW})$	15,000
$Replacement$ (\$)	10,000
$Operation\ \&\ Maintenance\ (\frac{\$}{year})$	500
$Hub\ Height\ (m)$	50
$Turbine\ Losses$ (%)	15
$Power\ Factor$	0.14
$Lifetime\ (years)$	25
AC/DC CONVERTER	
$Capacity\ (kW)$	1.0
$Capital\ (\frac{\$}{kW})$	300
$Replacement$ (\$)	300
$Nominal\ Efficiency$ (%)	95
$Lifetime$	15

The following points need to be addressed about Table 6 and the further case study in the next chapter:

1. Residential electric load is downloaded within HOMER Software. The software works on a specified location that is assigned at the beginning of the simulation and downloads the mean electricity usage of a regular household. This same load is used in the hand calculations, and location specified for this example is Northern Cyprus.
2. For the solar calculations, solar panels are assumed to be flat with no ground reflectance. Also, panels have no tracking systems with 25-degree tilt angle and 0 surface azimuth angle. The derating factor used by HOMER Software is directly equal to the losses due to real life conditions such as soiling, dust, and snow.

3. As mentioned before, the wind turbine power curve is what manufacturers depend on to detect the power output at definite wind speeds. The following figure shows the wind power curve of a 10 kW turbine with assumed values. Total turbine losses are assumed to be 15%.

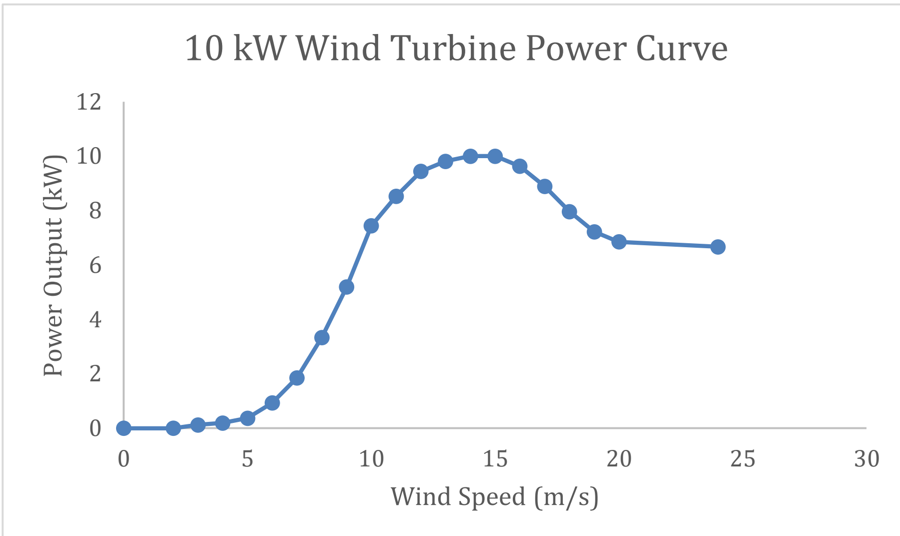

Figure 15: Wind Turbine Power Curve

4. Simple rates are used in the grid. Net metering and feed-in tariffs will not be considered in this part of the research. Emissions from the grid will be considered as a whole rather than calculating each greenhouse emission on its own. The minimum renewable energy fraction specified for this calculation in HOMER is 70%.

Moreover, with the information given above about the solar/wind hybrid on-grid system, manual calculations are made using equations (1-20) to obtain the LCOE and NPC, along with other valuable information shown in Table 7.

Table 7: Manual Calculation Results

Calculation	Value
NPC (\$)	36,225
$LCOE\ (\frac{\$}{kWh})$	0.201
$PV\ Production\ (\frac{kWh}{year})$	5,817
$Wind\ Turbine\ Production(\frac{kWh}{year})$	5,330
$Grid\ Production\ (\frac{kWh}{year})$	1,500
$Renewable\ Fraction$ (%)	85
$Greenhouse\ Emissions\ (\frac{kg}{year})$	-2,923

The same solar, wind, and converter inputs were inserted to HOMER software. Since the software's aim is to optimize the given system, it showed that the use of wind turbines is not feasible in this example. It acknowledges that wind speeds are not strong enough to induce a major difference in the hybrid system. Therefore, the optimized system only consists of a solar panel, converter, and the grid. Table 8 shows the values of the optimized system done by HOMER.

Table 8: HOMER Optimized System

Calculation	Value
NPC (\$)	15,213
$LCOE\ (\frac{\$}{kWh})$	0.110
$PV\ Production\ (\frac{kWh}{year})$	5,817
$Wind\ Turbine\ Production(\frac{kWh}{year})$	0
$Grid\ Production\ (\frac{kWh}{year})$	2,239
$Renewable\ Fraction$ (%)	71.2
$Greenhouse\ Emissions\ (\frac{kg}{year})$	-902

Table 8 shows a lower LCOE than Table 7 because wind speeds using the TMY values in Northern Cyprus are not dense enough to make a 10 kW turbine feasible. Therefore, it would make more sense to have a solar on-grid system to supply the power. Furthermore, one last simulation will be done in this example to verify that HOMER always optimizes the given inputs. This time, the cost of electricity from the grid will be decreased below the LCOE given in Table 8 to examine if the software will only choose the grid connection alone. The cost of electricity will be reduced to 0.09 $(\frac{\$}{kWh})$ with the same inputs. Table 9 will show the result.

Table 9: HOMER Results with Lower Cost of Grid Electricity

Calculation	Value
NPC (\$)	6,563
$LCOE\ (\frac{\$}{kWh})$	0.09
$PV\ Production\ (\frac{kWh}{year})$	0
$Wind\ Turbine\ Production(\frac{kWh}{year})$	0
$Grid\ Production\ (\frac{kWh}{year})$	4,109
$Renewable\ Fraction$ (%)	0
$Greenhouse\ Emissions\ (\frac{kg}{year})$	-2,613

Indeed, the software chooses the most feasible solution which is to completely depend on the electricity grid. After acknowledging that the software optimizes any given input, the next chapter will discuss and compare different examples of using a solar/wind/fuel cell system hybrid system.

Chapter 4 - Case Study

This chapter will present an overview of the location of METU NCC and why it should be a valid example as a case study. Solar and wind data sources will be discussed along with the electricity demand of a regular household included within the campus parameter.

METU NCC campus location is of vital importance to this case study. It lies in the northern part of Cyprus and has a climate that corresponds to a Mediterranean climate. Due to this climate, hot summers are usually noted with global horizontal insolation (GHI) of 5.48 $kWh/_{m^2}$ near the location of the campus, which corresponds to readings higher than Spain (5.35 $kWh/_{m^2}$), and just lower than USA (6.03 $kWh/_{m^2}$) and Africa (6.43$kWh/_{m^2}$) [64]. As high as the solar energy potential is in Northwest Cyprus, the island still depends on oil-based generators as the main supply of electricity, which directly means that the campus depends on non-renewable imported sources to supply energy. Figure 16 shows the GHI in North Cyprus and indicates that the position of METU NCC (Guzelyurt) has high solar potential.

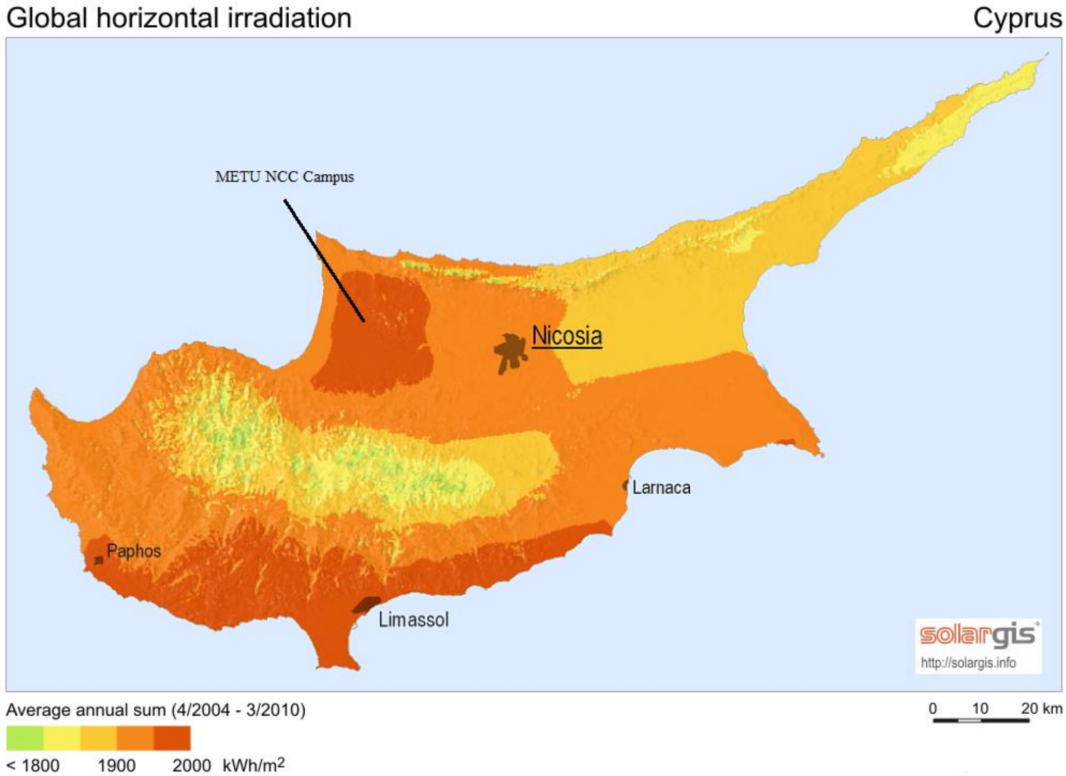

Figure 16: GHI in Cyprus [68]

The location of METU NCC is relatively isolated with a high electricity demand and promising renewable resources. The population on-campus in 2017 has exponentially increased since the opening of the university. Students are looking for dormitories off-campus due to the intense crowdedness. Although this case study will only include energy calculations for a household on campus, enhancing social, financial, and environmental issues for dormitories can be done for further research. This self-contained community demands electricity 24 hours a day, seven days a week. The electricity is supplied to the campus by regular, carbon emitting means of power generation such as imported fuel based generators and backup diesel generators. This dependency on fossil fuels decreases the security of energy generated causing pollution from greenhouse emissions and noise, and high electricity bills. The advantageous reasons behind establishing a REMG are the following:

1. Long term economic growth.
2. Environmental enhancement through reduced greenhouse emissions.
3. Supporting research programs and other educational activities.
4. Community level grid size as a long term goal.
5. Strengthening the “green campus” role.

However, there are some set-backs for undergoing this type of project, and those are:

1. Available land to install REMG.
2. Relatively unstable and weak electricity grid.
3. Uni-directional metering.
4. Capital Cost.

Uni-directional metering is a term that indicates that all electricity generated by any type of renewable energy source or micro-grid that exceeds the demand and storage must be fed back to the grid with no economic advantage whatsoever. Hence, producing excess electricity will not be of any benefit to the project or the university. However, a counter move is to use certain schemes like feed-in tarrifs or net-metering that can only contrast uni-directional metering. However, net metering will not be included in the case study. REMG models are not strangers to METU NCC campus due to the available solar and wind resources. Solar resources have been monitored using pyranometer and pyrheliometer for GHI and Direct Normal Insolation (DNI), respectively. GHI and DNI have been measured since 2010 and 2013, respectively. Wind speeds were also monitored at different heights. Readings at heights of 2,30,40, and 50 meters were measured.

Furthermore, a 1 MW solar plant was installed in February 2016 and that power is almost equal to the average electricity demand of the campus.

Renewable Resources at METU NCC

Renewable resources in METU mainly depend on the TMY values that are retrieved from Meteonorm [57]. For this case study, the Direct Normal Irradiation (DNI), Global Horizontal Insolation (GHI), dry bulb temperature, wind direction, and wind speeds are to be considered. Wind turbines are considered to have less potential in terms of renewable energy generation than solar panels due to the low and variable winds at the location of campus. However, according to European Wind Classification, Northern Cyprus is a moderately windy region [70]. Figure 17 shows the monthly average wind speed data adapted from TMY values at a height of 10 meters.

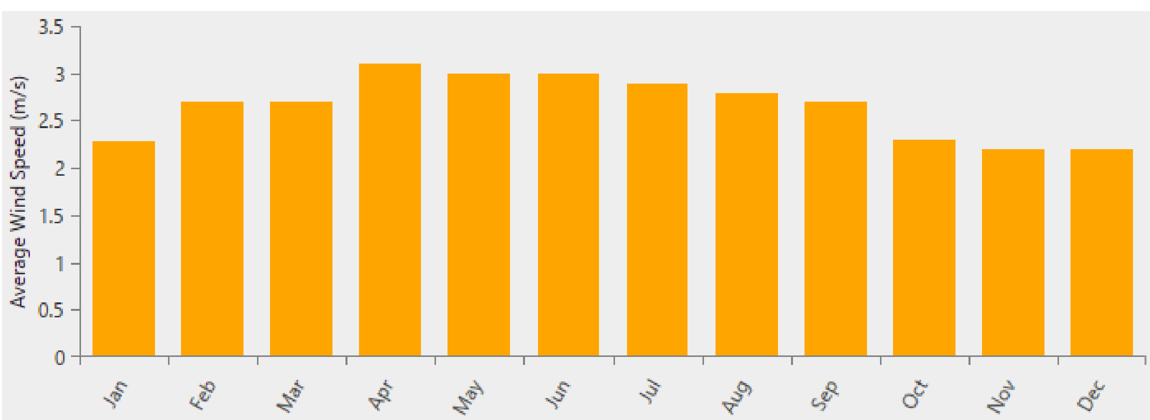

Figure 17: Average Monthly Wind Speeds in TRNC

The highest and lowest magnitudes occur in April and November, respectively. The highest and lowest wind speeds are 3.104 m/s and 2.195 m/s, respectively, with an annual average of 2.65 m/s. As mentioned before, there must be an assumption with a power factor to have a representation of what the wind speeds might be at positions alternative to the position of the height of measurement. The power factor that is assumed here is 0.14, and the following Figure 18 shows how power produced differs with hub height of a wind turbine.

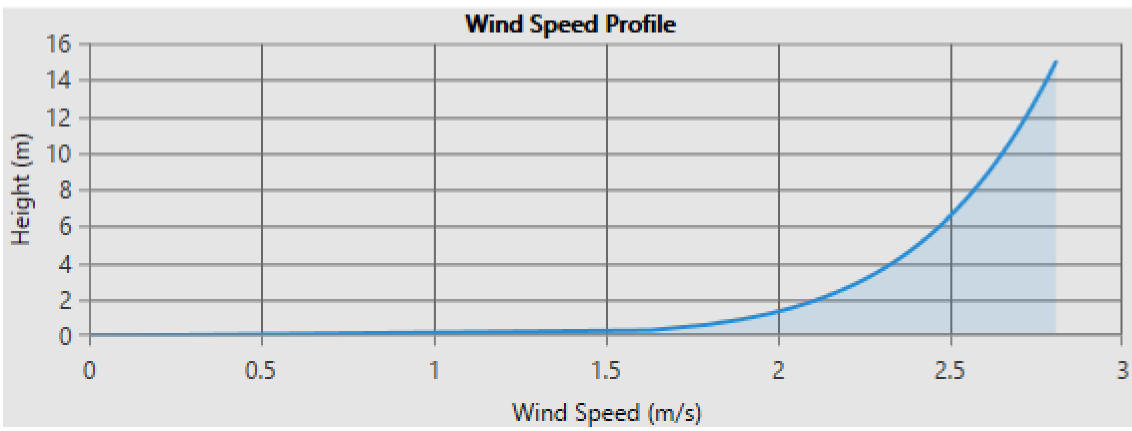

Figure 18: Wind Speed Profile for 0.14 Power Factor

The average hourly wind speed at 10 meters is 2.81 m/s and throughout the year, the frequency in which wind speeds exceed this average is almost 40%.

Moreover, solar energy, the more common source of renewable energy in Northern Cyprus, shows higher effectiveness in this hot, sunny region of the world. Figure 19 and 20 show the monthly average Global Horizontal Insolation and Direct Normal Irradiation, respectively, claimed from TMY values in Northern Cyprus. The average annual GHI and DNI are 4.96 kWh/m2/day and 5.19 kWh/m2/day.

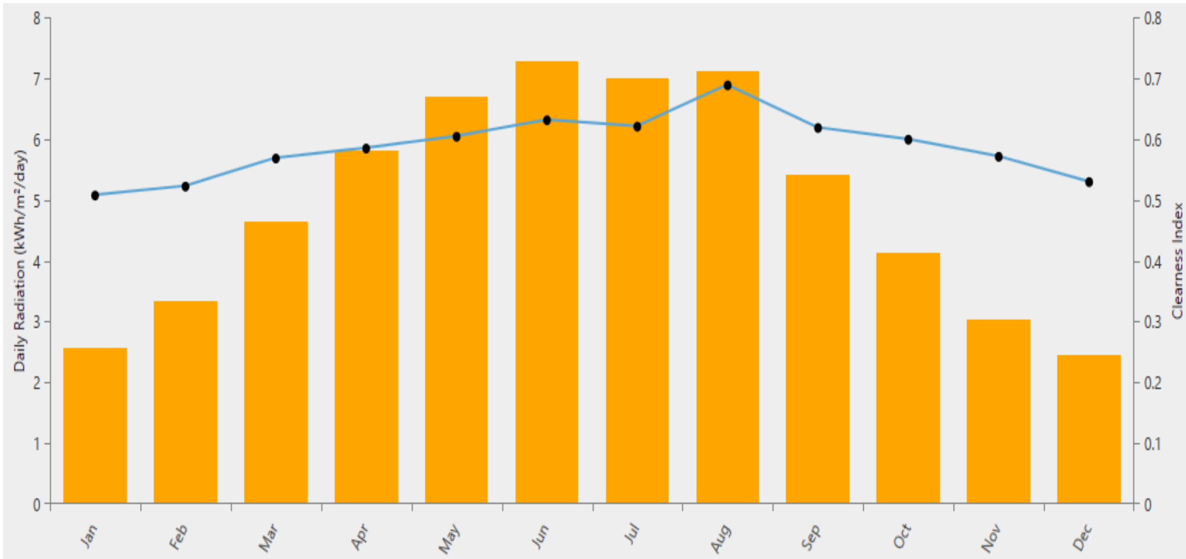

Figure 19: Daily GHI Vs. Month Vs. Clearness Index

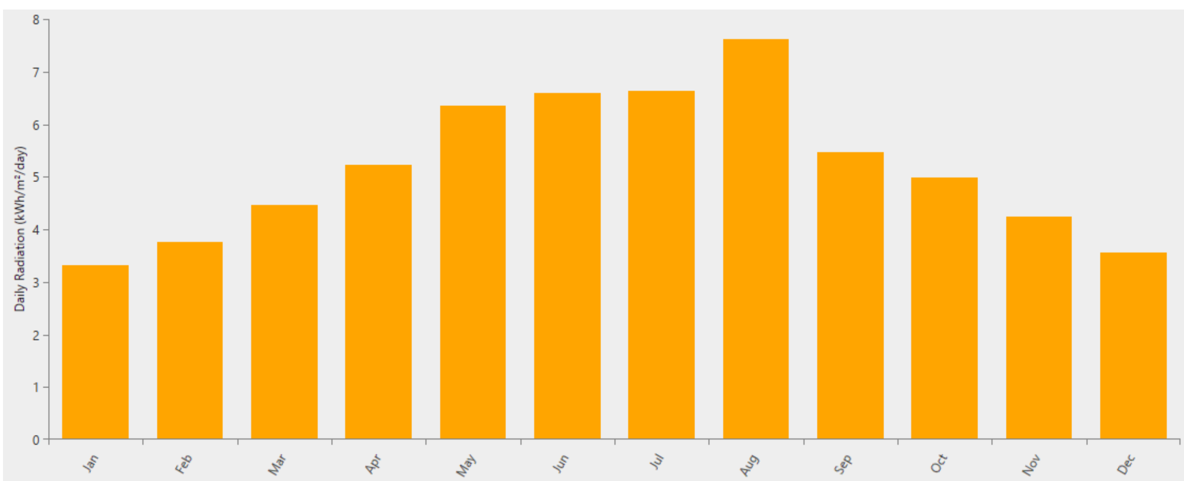

Figure 20: Daily DNI Vs. Months

Furthermore, temperature is also noted from the TMY values and drawn in a bar graph. The monthly averages of each year is recorded and the highest temperature occurs in July with a value of $29.24°C$, whereas the lowest temperature occurs in January at

10.90°C. Figure 21 shows how temperature varies with different months of the year and indicates that there is only one peak value which happens in summer days. The average yearly temperature is 19.76°C.

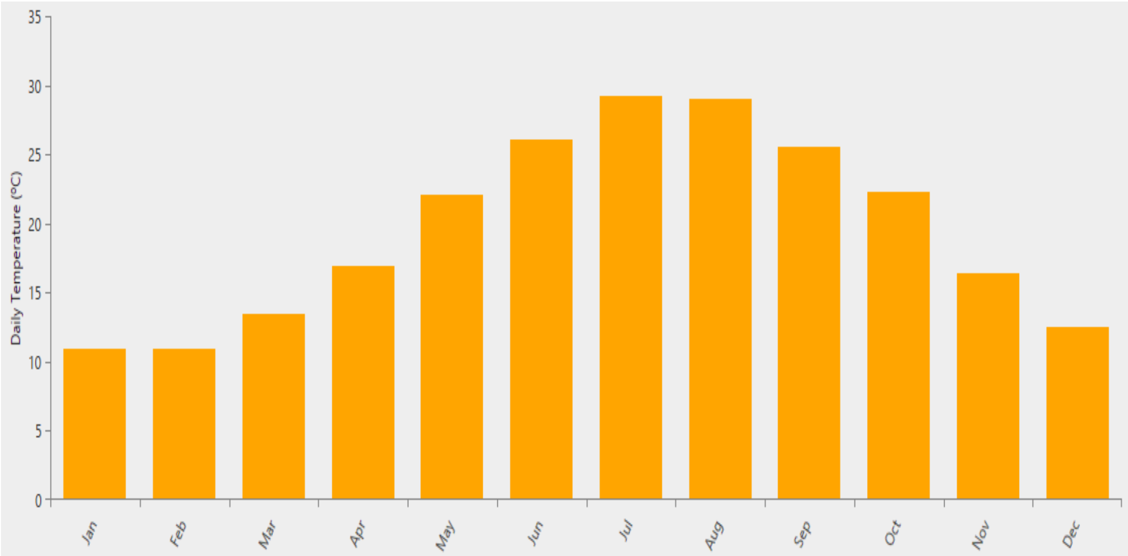

Figure 21: Temperature Vs. Months

Using the given renewable energy data, a correct simulation can be undertaken to perform an economic and environmental analysis on a household in the location of METU NCC.

However, some points need to be addressed:

1. The values for DNI and GHI in Figures 18 and 19 are somewhat incredible in the months of September and October. Their values should be higher than the given readings. That is most probably due to errors in recording.
2. The TMY values for wind speeds might have a great deviation from the actual measured data. That is due to the fact wind speeds in METU NCC are measured

from 10-meter-high cliff which is located in a position with great potential for wind speeds.

3. The solar, wind, and temperature inputs are assumed as constant. In other words, the extreme change in climate will not be considered as a part of this project. Forecasting will include a wide variety of variables that will contain more than 400,000 simulations.
4. The methodology for input is not necessarily restricted to this area. It can be applied to any location worldwide as long as TMY data is provided or any other sort of measured data.

Demand Data

As for the demand of a household in METU, HOMER software downloads a series of hourly demand data formulated and combined in the form of monthly averages to give out an AC Electric Load. This is a synthetic load that meets the demand criteria of the specified location in the given year. It is as near to an actual load as a software can possibly simulate. Table 10 shows the metrics of the electric load and their values.

Table 10: Electric Load Parameters

Metric	Value
Load Type	AC
Average $(\frac{kWh}{day})$	11.27
Average (kW)	0.47
Peak (kW)	2.39
Load Factor	0.2
Time Step (Minutes)	60

Although the peak month is July, Figure 22 shows that other seasonal peaks happen in April and November. Electric peak in April is at 1.94 kW while the peak that happens at the beginning of a winter season in November is at 1.88 kW.

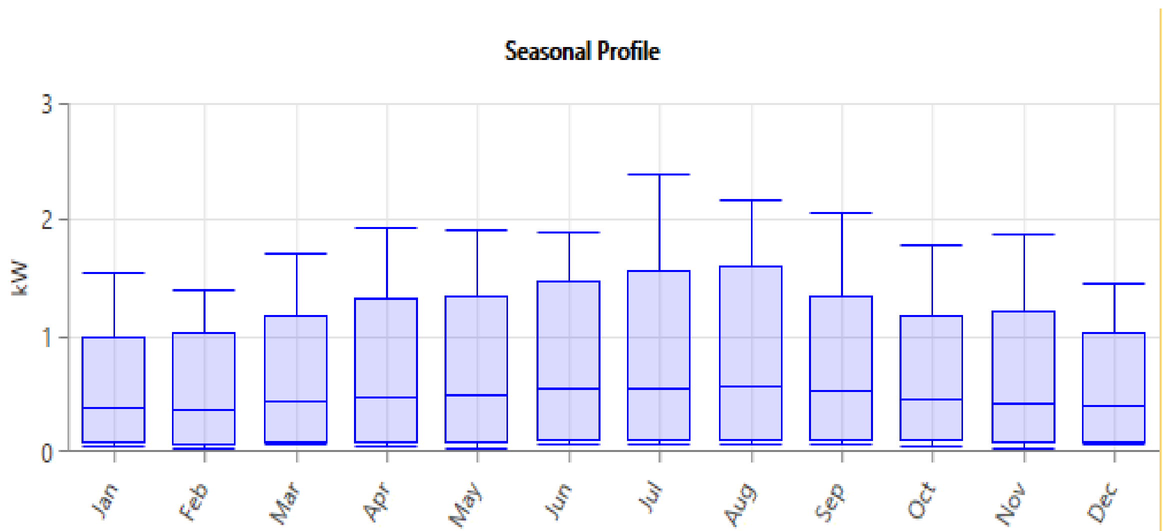

Figure 22: Electric Load Seasonal Profile

To show a more valuable estimation for the calculations and a better understanding of the demand, Figure 23 and 24 display the hourly electrical demand at any given point of the year and a frequency distribution histogram of the needed power of each day of the year, respectively.

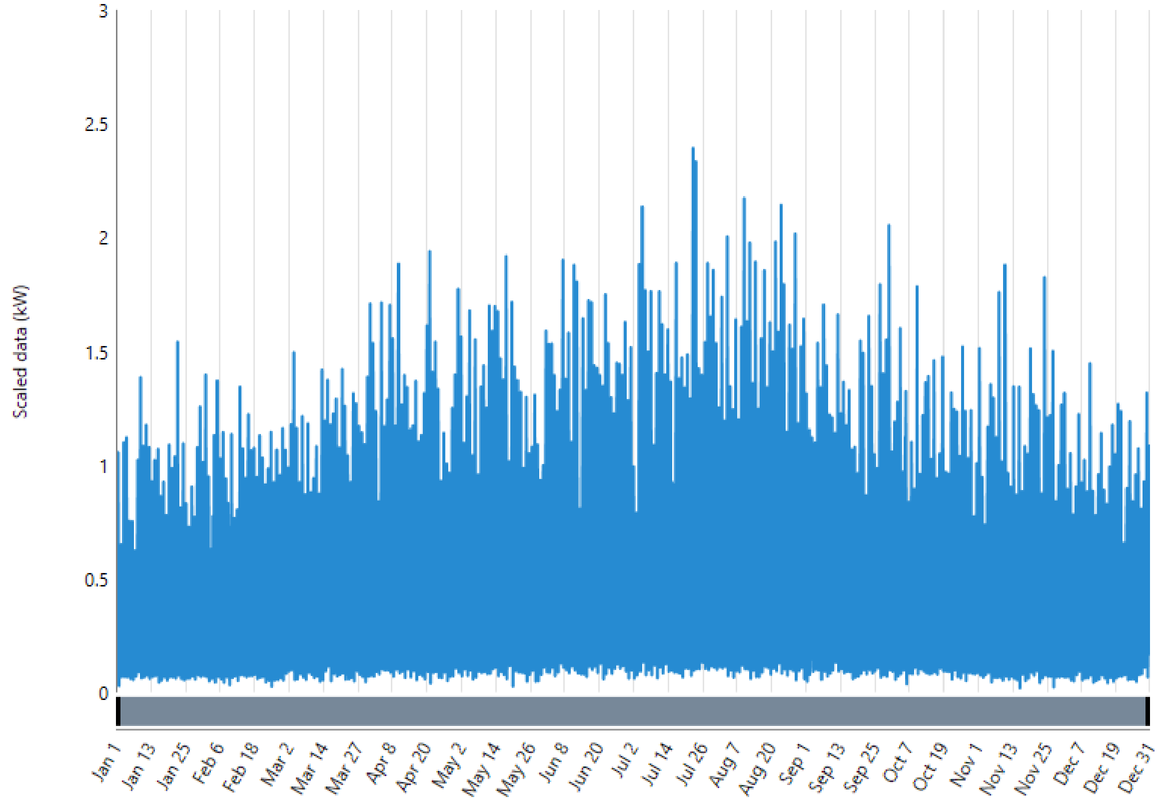

Figure 23: Hourly Demand for Electricity

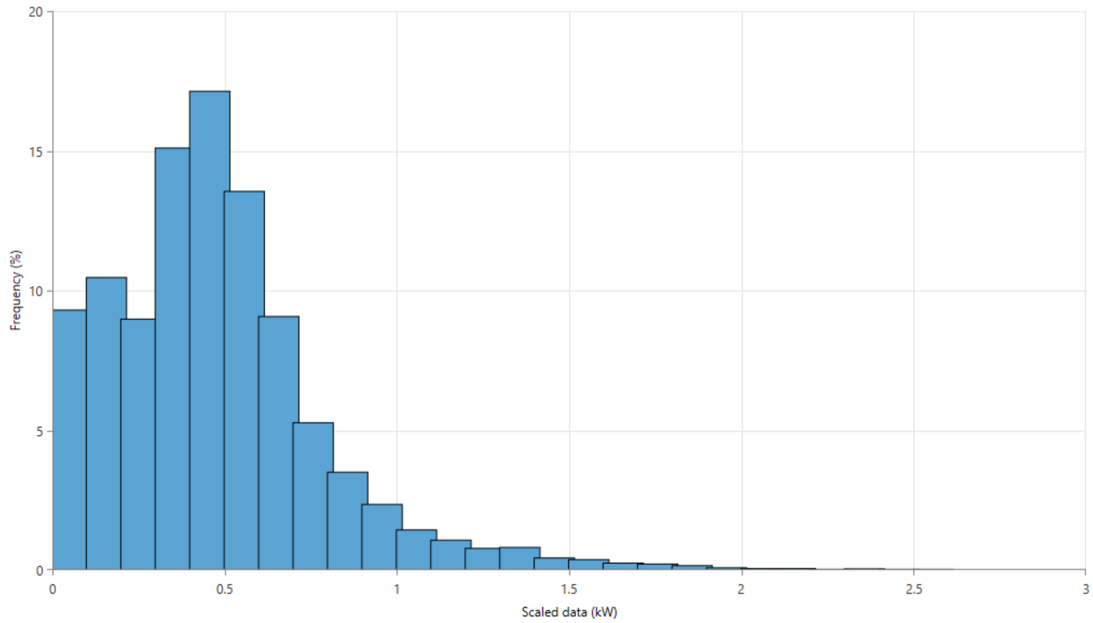

Figure 24: Frequency Vs. Scaled Data

Figure 23 demonstrates that the maximum frequency of demand is around 17.5% with a daily demand of 0.5 kW. The 0.5 kW can also be interpreted as the minimum load, or the base load, needed each day to be supplied by the input system. The following chapter will show the results of using this data to come up with an optimal system.

System Parameters

Table 11 will summarize the system parameters that will be used in the case of METU NCC. The capacity values were assumed as the maximum power that is needed for each of the solar, wind, and fuel cell systems if they were each used singularly.

Table 11: Parameters for Case Study in METU NCC

PARAMETERS	
RESIDENTIAL ELECTRIC LOAD	
$Average\ (\frac{kWh}{day})$	11.26 [47]
$Average\ (kW)$	0.47 [47]
$Peak\ (kW)$	2.09 [47]
$Load\ Factor\ (\%)$	0.22 [47]
SIMPLE RATE GRID	
$Grid\ Power\ Price\ (\frac{\$}{kWh})$	0.150 [47]
$Greenhouse\ Emissions\ (\frac{g}{kWh})$	636.08 [47]
FLAT PLATE SOLAR PANEL (DC)	
$Capacity\ (kW)$	(0-5) (+0.5)
$Capital\ (\frac{\$}{kW})$	1,800 [71]
$Replacement\ (\$)$	1,500 [71]
$Operation\ \&\ Maintenance\ (\frac{\$}{year})$	10 [71]
$Nominal\ Operating\ Temperature\ (°C)$	47 [71]
$Nominal\ Efficiency\ (\%)$	16 [71]
$Temperature\ Effects\ (\frac{\%}{°C})$	-0.50 [71]
$Derating\ Factor\ (\%)$	80 [47]
$Lifetime\ (years)$	25 [71]
WIND TURBINE (DC)	
$Capacity\ (kW)$	0-10
$Capital\ (\$)$	5,000 [72]
$Replacement\ (\$)$	2,000 [72]
$Operation\ \&\ Maintenance\ (\frac{\$}{year})$	500 [72]
$Hub\ Height\ (m)$	50
$Turbine\ Losses\ (\%)$	15 [72]
$Power\ Factor$	0.14 [72]
$Lifetime\ (years)$	25 [72]
AC/DC CONVERTER	
$Capacity\ (kW)$	0-4
$Capital\ (\frac{\$}{kW})$	5 [47]
$Replacement\ (\$)$	2 [47]
$Nominal\ Efficiency\ (\%)$	95 [47]

$Lifetime$	15 [47]
Fuel Cell Generator (DC)	
$Capacity\ (kW)$	0-5 (+0.2)
$Capital\ (\frac{\$}{kW})$	2,400 [73]
$Replacement\ (\$)$	2,000 [73]
$Fuel\ Resource$	Stored Hydrogen
$Lifetime(hours)$	4,000 [73]
Electrolyzer (DC)	
$Capacity\ (kW)$	0-5
$Capital\ (\frac{\$}{kW})$	300 [47]
$Replacement\ (\$)$	300 [47]
$Nominal\ Efficiency\ (\%)$	85 [47]
$Lifetime$	15 [47]
$Minimum\ Load\ Ratio\ (\%)$	85 [47]
Hydrogen Tank	
$Size\ (kg)$	0-50 (+5)
$Capital\ (\frac{\$}{kg})$	13 [35]
$Replacement\ (\$)$	0

Chapter 5 - Results and Discussion

This chapter will demonstrate the methodology explained in Chapter 3 along with HOMER Software to introduce the optimum system. The chapter will include subsections that will present the results in terms of configuration, performance, RES fraction, greenhouse emissions, LCOE, NPV, and the energy generated from each component individually. The chapter will be classified into two major sections which are On-Grid Systems and Off-Grid Systems. Each section will have subsection calculation and evaluation to finally conclude with an optimal system On-Grid and Off-Grid. For the Grid, no net-metering of feed-in tariffs are considered to avoid confusion and inaccurate results.

Off-Grid System

As this case study is concerned with adding a new rising renewable energy source to a hybrid system, which is the fuel cell system in this case, the fuel cell system will be modeled on its own in the beginning to prove that it will not be feasible to apply it without any other renewable or non-renewable energy sources alongside it. HOMER Software has a special way of modelling fuel cell systems. The fuel cell is modelled as a typical generator with stored hydrogen as the supplied fuel. Hydrogen gas can either be generated from an electrolyzer or reformer. The reformer is usually fed a common gas such as diesel that is then transformed into hydrogen and other end products that need to be dealt with as well. Therefore, an electrolyzer will be used. Also, hydrogen needs to be stored in a hydrogen tank and then supplied to the fuel cell itself. Therefore, a hydrogen tank is also needed in the fuel cell system. Furthermore, the electrolyzer needs a source of electricity in order to produce hydrogen from the electrolysis process. This leads to the conclusion that the fuel cell system cannot be modelled by itself in the program because the source of electricity that supplies the electrolyzer is normally another form of renewable energy that depends on itself. Now, three cases can be made to see how the fuel cell system cooperates in a hybrid system. A solar panel/fuel cell system, a wind turbine/fuel cell system, and a solar/wind/fuel cell system hybrid system will be optimized. However, due to the weather conditions in METU NCC, the sun is much more effective than the wind. Therefore, HOMER calculates that the most feasible solutions all contain solar panels. With that said, there are only the case of solar/fuel cell system and the combination of all three of them. Also, hypothetical, futuristic, and different location cases will be done.

Solar/Fuel Cell System

Out of 39,000 simulations, the optimal design for a solar/fuel cell system can be described as the least favored combination of the two. It shows more than 0.5 $/kWh as an LCOE and has a NPC of $16,587. The hybrid system consists of:

1. 3 kW Solar Panel
2. 0.1 kW Fuel Cell Generator
3. 1 kW AC/DC Converter
4. 1 kW Generic Electrolyzer
5. 5 kg Hydrogen Tank

Table 12 will show the important results of this calculation.

Table 12: Solar/Fuel Cell Optimal Combination

Calculation	Value
NPC (\$)	16,587
$LCOE\ (\frac{\$}{kWh})$	0.5261
$PV\ Production\ (\frac{kWh}{year})$	5,795
$Fuel\ Cell\ Production(\frac{kWh}{year})$	510
$H_2\ from\ Fuel\ Cell\ (\frac{kg}{year})$	30.6
$H_2\ from\ Electrolyzer\ (\frac{kg}{year})$	35.6

As seen from Table 12, the LCOE is exactly 0.5261 \$/kWh, which is more than 3 times the cost of electricity from the grid in Northern Cyprus. Even with greenhouse emission penalties, the cost is still too high. Moreover, Figure 25 shows the average electric production of the solar panel and fuel cell.

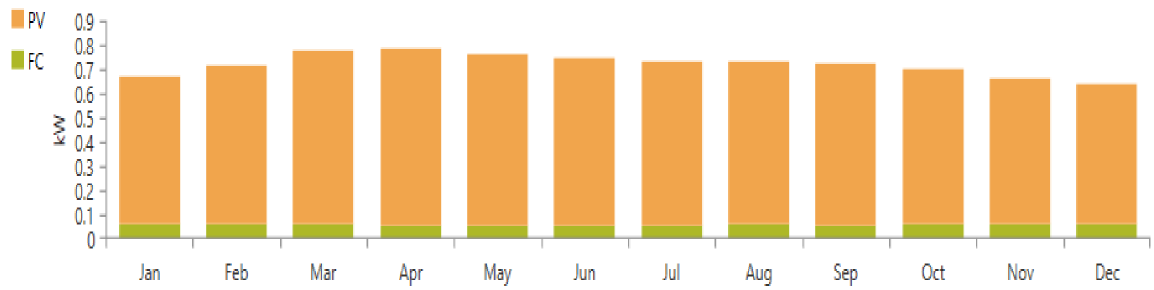

Figure 25: Solar/Fuel Cell Average Monthly Production

As seen from Figure 25, the fuel cell system acts as a generator to supply the remaining load for the hybrid system. It does not reach more than 0.1 kW on average per month. Figure 26 shows the amount of average hydrogen produced per month to have a better understanding of how much extra power is needed to meet the total demand.

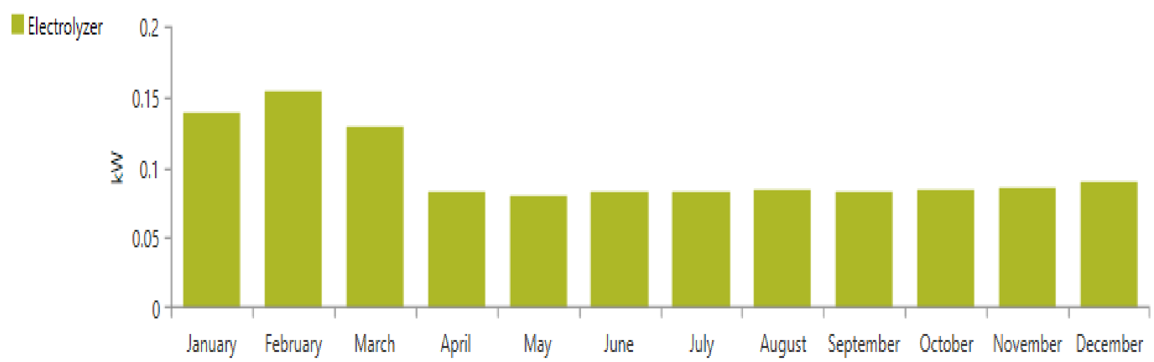

Figure 26: Electrolyzer Average Hydrogen Production

It is also important to note that the LCOE of the solar panel in this hybrid system, with the total amount of working hours and electricity produced, is equal to 0.0773 $/kWh. This proves that the fuel cell system is still too expensive.

Solar/Wind/Fuel Cell System

The combination of the three renewable energy sources and how to make it feasible is one of the major aims of this study. However, making it become as such is relatively difficult when compared to an On-Grid situation where the LCOE is cheaper. On the other hand, in some locations around the world, the electricity grid is not stable or not found at all. The optimal Off-Grid hybrid system of these three renewables has an LCOE of 0.3418 $/kWh and an NPC of $11,435. The hybrid system consists of:

1. 2 kW Solar Panel
2. 3 kW Wind Turbine
3. 0.1 kW Fuel Cell
4. 2 kW System Converter
5. 4 kW Generic Electrolyzer
6. 5 kg Hydrogen Tank

The first realization made before looking at the final calculations is the choice of capacity. It does make sense to see that the fuel cell has the lowest capacity because it has the highest overall cost. The focus is on the solar and wind resources as expected. However, the price is still more than double the price of regular grid electricity. Table 13 will show the important readings out of this system.

Table 13: Solar/Wind/Fuel Cell System Optimal Combination

Calculation	Value
NPC (\$)	11,435
$LCOE\ (\frac{\$}{kWh})$	0.3418
$Wind\ Production(\frac{kWh}{year})$	2,914
$PV\ Production\ (\frac{kWh}{year})$	3,863
$Fuel\ Cell\ Production(\frac{kWh}{year})$	2.45

It is interesting to see that HOMER is optimizing to an extent where the fuel cells are only producing a total of 2.45 kWh/year. It shows that the most expensive part of the hybrid system is minimized to obtain the most feasible solution. Figure 27 shows the power production from the different sources and Figure 28 shows when the 2.45 kWh of Fuel Cell power is used throughout the year.

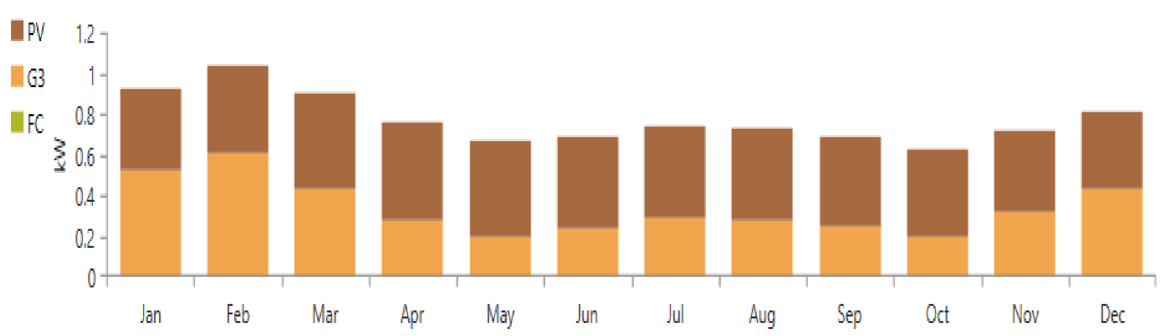

Figure 27: Solar/Wind/Fuel Cell Power Sources

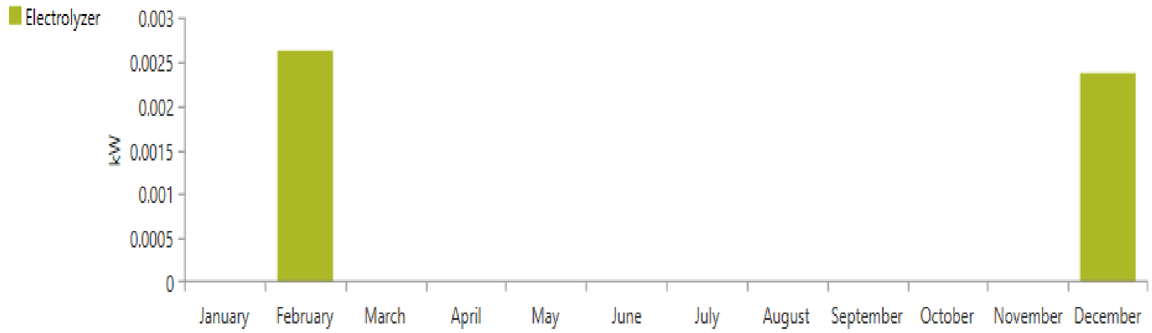

Figure 27: Monthly Hydrogen Usage

Even when the fuel cell is working in February and December, the power produced is negligible to the total power demanded in the two months. Figure 27 shows very clearly that little-to-no fuel cell power is produced.

Reduction in Fuel Cell Generator Cost

The following analysis will be a hypothetical example about reducing the cost of the fuel cell generator to a point where it equals the cost of the solar panel. In this example, the fuel cell generator cost will be reduced to 1800 $/kW rather than 2400$/kW. Due to the solar energy playing a more feasible role in METU NCC and Northern Cyprus in general, reducing the cost of fuel cell generators to that extent might cause the solar panels to be replaced in the optimized system. Another scenario that might happen is the replacement of a wind turbine. Knowing that wind speeds at METU NCC are not high naturally, the latter scenario is the most probable one. Note that the price of hydrogen per kilogram and electrolyzer are not tampered with. Table 14 shows the results of simulating this hypothetical example. The system consists of:

1. 2 kW Solar Panel

2. 0.3 kW Fuel Cell Generator
3. 1 kW Electrolyzer
4. 1 kW AC/DC Converter
5. 5 kg Hydrogen Tank

Table 14: Optimal System with Reduced Fuel Cell Generator Cost

Calculation	Value
NPC ($)	8,424
$LCOE\ (\frac{\$}{kWh})$	0.2918
$Wind\ Production(\frac{kWh}{year})$	0
$PV\ Production\ (\frac{kWh}{year})$	4,317
$Fuel\ Cell\ Production(\frac{kWh}{year})$	393

The LCOE now stands at 0.2918, which is less than twice the electricity grid LCOE (0.150). Figures 27 and 28 show the monthly hydrogen production from the electrolyzer and the monthly fuel summary, respectively.

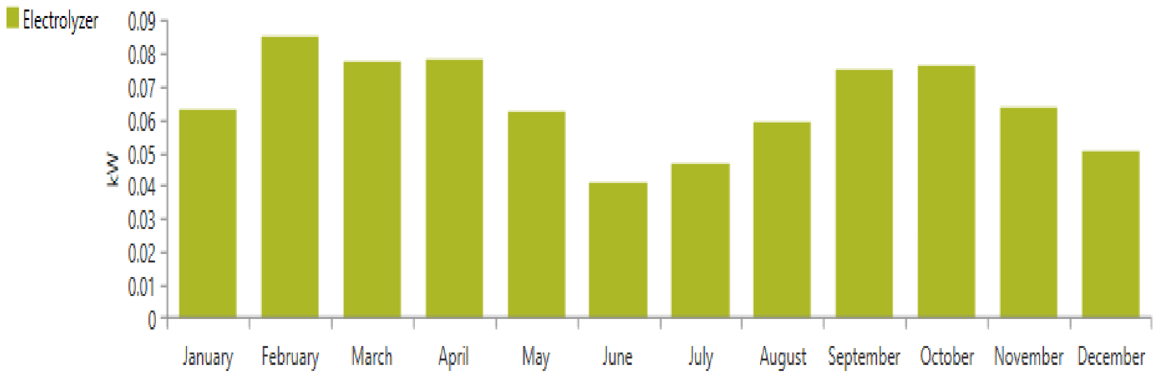

Figure 28: Monthly Hydrogen Production

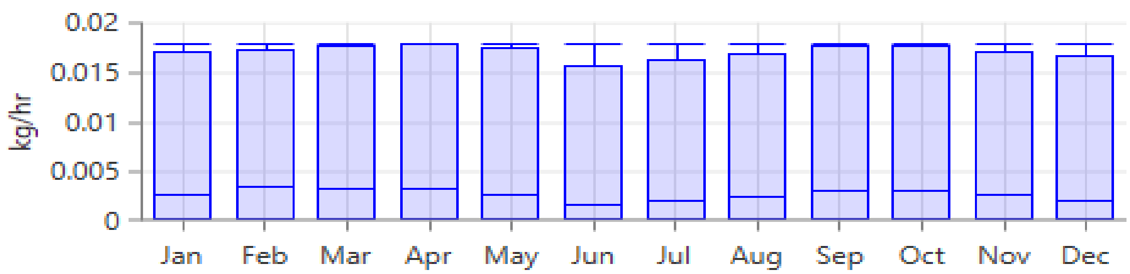

Figure 29: Hydrogen Fuel Summary

The impact of equalizing the cost of fuel cell generators and solar panels is that the optimized system becomes free of wind turbines. The noticeable LCOE reduction is due to a 600$/kW decrease in fuel generator price, and that led to the fuel cell system to be more economical as a whole. Also, wind turbines are more harmful to the environment in terms of the total area and noise that comes along with them. Therefore, this hypothetical example shows that the combination is economically and environmentally friendlier.

Future Cost Hypothesis

This is another hypothetical cost example to be analyzed. However, all three renewable energy sources will be considered and adjusted this time around. Many authors suggest future goals for solar, wind, and fuel cell system costs. According to [71], solar panel prices already dropped to 1000$/kW in 2017. By 2030, the cost per kW will decrease by at least 20%, meaning that the cost will become 800$/kW. The author also adds that this residential price drop will beat the governmental goal by three years. In another study by the Distributed Wind Energy Association [72], small farm residential wind turbine goals are set to be at a capital of $4,500 by 2030. On the other hand, CHP's for small scale or residential systems cannot be reduced to 1000$/kW, even at this fast rate of progress [73]. It is now assumed that the capital cost of the fuel cell system will decrease by 400$/kW in 2030. Therefore, solar, wind, and fuel cell system will have a capital of 800$/kW, $4500, and 2000$/kW, respectively. Table 15 will show the results for this hypothesis.

Table 15: Results for Future Renewable Costs

Calculation	**Value**
NPC (\$)	5,817
$LCOE\ (\frac{\$}{kWh})$	0.2228
$Wind\ Production(\frac{kWh}{year})$	0
$PV\ Production\ (\frac{kWh}{year})$	10,793

$Fuel\ Cell\ Production (\frac{kWh}{year})$	0

The system consists of a single 5 kW solar panel with a 1 kW AC/DC converter. As seen from the table, the decrease in price per kW of solar panels along with solar energy numbers in METU NCC reveal that a solar system on its own is the most feasible. Also, this shows that no matter how much the prices of fuel cells and wind turbines go down, solar panels will always dominate the category of renewables in Northern Cyprus and in METU NCC in particular.

LCOE Reduction to Grid Cost

It is nearly impossible to implement an off-grid system with the three renewable energy sources in the case study. As impossible as it is, an attempt to reduce the cost of fuel cell systems is made without changing the futuristic costs of solar and wind power production. The only LCOE result that nearly equaled the LCOE of the common grid occured when the fuel cell system cost went down to an unrealistic 100$/kW. The system includes:

1. 2.5 kW solar panel
2. 3 kW wind turbine
3. 1 kW fuel cell generator
4. 2 kW electrolyzer
5. 1 kW AC/DC converter
6. 20 kg hydrogen tank

Table 16 will show the LCOE, NPV, and power output from each source. Figure 30 will show the monthly average power production.

Table 16: Closest Results of Optimal Hybrid System to LCOE of Grid

Calculation	**Value**
$NPC\ (\$)$	7,885
$LCOE\ (\frac{\$}{kWh})$	0.153
$Wind\ Production(\frac{kWh}{year})$	2,914
$PV\ Production\ (\frac{kWh}{year})$	5,397
$Fuel\ Cell\ Production(\frac{kWh}{year})$	2,012

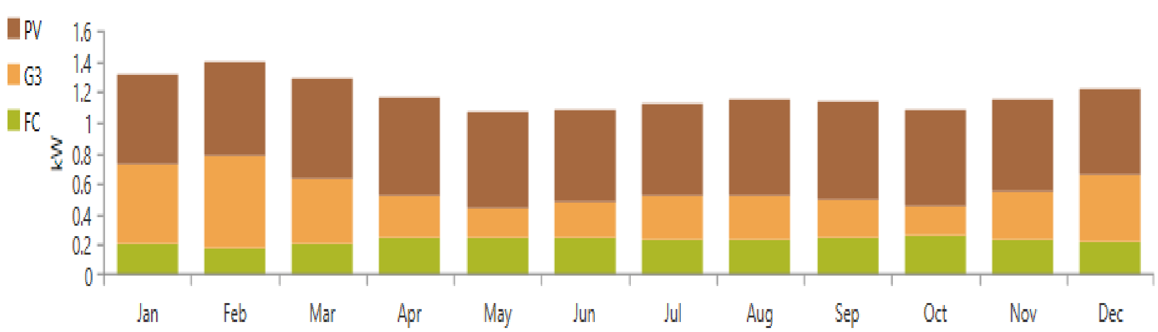

Figure 30: Monthly Average Power Production

With all the decrease in capital cost of the fuel cell system, the LCOE of the grid is still cheaper than the hybrid system with the fuel cell generator cost at only 100$/kW.

On-Grid System

In the case of on-grid systems, it would make sense that the LCOE of the optimal combination of renewables would be much cheaper than off-grid systems. The reason behind it is simply because the electricity grid itself has an LCOE of around 0.150 $/kWh in Northern Cyprus. Renewable sources have a higher LCOE on their own. However, the combination and optimization of such renewables may yield different values. For on-grid systems, the case of modelling the fuel cell system along with the grid can be done as the electrolyzer is capable of receiving power from the grid itself to transform water into hydrogen and feed it to the fuel cell generator. Nevertheless, HOMER optimizes the given system and chooses the lowest LCOE and NPC which is the grid by itself with the normal LCOE of 0.150 $/kWh. Actually, the software suggests that it is not feasible at all to include a fuel cell system along with a power grid. The reason behind that is the high cost per kW of the fuel cell generator (2400$/kW). The capital cost of the electrolyzer and hydrogen tank are not inclusive in the cost of the fuel cell generator as well, which adds even more to the total capital cost. Hence, simulations are done for an electricity grid with 0.150 LCOE and no net-metering or feed-in tariffs accompanying a solar/fuel cell system and solar/wind/fuel cell system hybrids. When combined with solar panels or wind turbines, fuel cell systems are never feasible in HOMER software. This system is simply a combination of a 4 kW solar panel, 2 kW AC/DC converter, and the electricity grid. Table 17 will show the only feasible result of this trio when combined with grid power.

Table 17: On-Grid Single Optimal Hybrid System

Calculation	Value
NPC (\$)	8,049
$LCOE\ (\frac{\$}{kWh})$	0.1184
$Wind\ Production(\frac{kWh}{year})$	0
$PV\ Production\ (\frac{kWh}{year})$	3,238
$Grid\ Production\ (\frac{kWh}{year})$	2,283
$Renewable\ Penetration$ (%)	42.5

As stated before, HOMER never includes a fuel cell system in an on-grid calculation. Therefore, it is clear that the fuel cell power production is zero. Also, this table shows that solar power is strong enough to be feasible without any other source of renewable energy with it due to sunny location. The disadvantage is that there is no energy storage medium like if a fuel cell system included. Also, the renewable energy penetration is quite low if the customer thinking about the environmental aspect. The conclusion is that a fuel cell system is never the answer when a grid is present. In this case, even wind energy is not sufficient enough to be included in the optimal result.

Alternative Location Off-Grid Systems

The same methodology will be applied to a region other than METU NCC in Northern Cyprus. The location to be tested is in Beijing, China due to the thrive in renewables. Solar GHI and DNI, wind resources, and temperature will definitely change and will be accounted from HOMER's renewable resource library. The demand for the household will be the exact same power needed as the previous simulations. The cost for the renewable sources will also be the same as the original prices used for this year. In this example, the LCOE was much greater than 0.150 $/kWh, which is the cost of regular grid power. Table 18 shows the results of the optimal hybrid system and Figure x and y show the monthly average power production and average monthly hydrogen production, respectively. The system consists of:

1. 3.5 kW solar panel
2. 1 kW wind turbine (*2)
3. 2 kW fuel cell generator
4. 2 kW AC/DC converter
5. 3 kW electrolyzer
6. 50 kg hydrogen tank

Table 18: Results for China optimal hybrid system

Calculation	**Value**
NPC (\$)	35,326
$LCOE\ (\frac{\$}{kWh})$	0.7286

$Wind\ Production (\frac{kWh}{year})$	0
$PV\ Production\ (\frac{kWh}{year})$	3,238
$Grid\ Production\ (\frac{kWh}{year})$	2,283
$Renewable\ Penetration\ (\%)$	42.5

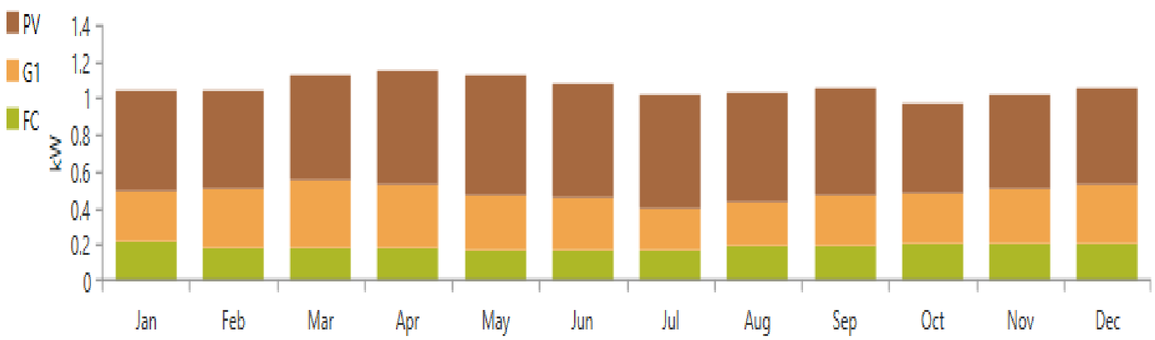

Figure 31: Average Monthly Power Production in China Example

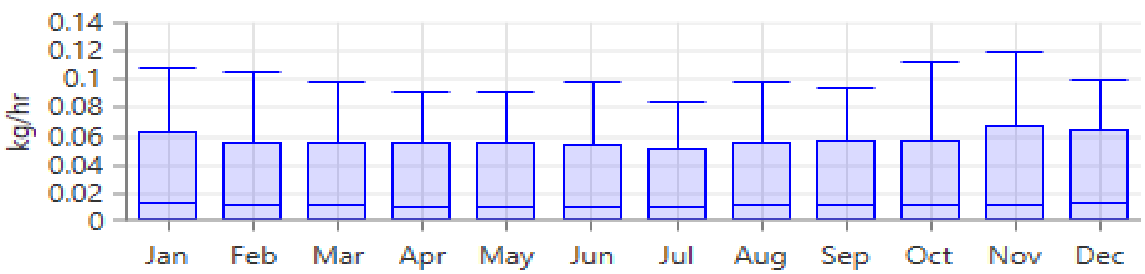

Figure 32: Average Monthly Hydrogen Production for Fuel Cell

It is crucial to understand that the location is a vital factor in optimizing a hybrid system. Solar resources in one place are not the same as solar resources in another. This is also true for all other renewable resources. The same inputs and prices were input to the system with the resources different and LCOE dramatically changed.

Chapter 5 - Conclusion and Future Work

Conclusion

An investigation is undergone on the feasibility and optimization of on-grid and off-grid renewable energy systems including solar, wind, and fuel cell system hybrid systems on a regular household. The models and equations used for each of the components are demonstrated in the methodology, and a case study is done on the campus of Middle East Technical University in Northern Cyrus. Synthetic TMY data values are used as a reference to solar DNI and GHI, wind velocity and direction, and temperature estimates. The demand for an average household consumption is downloaded from a 2017 source in HOMER Pro Software, which is the program used to simulate thousands of simulations with multiple variables and sensitivity analysis to conclude with optimal combinations. Based on the proposed results by the software, an off-grid fuel cell system is not able to produce energy on its own because it needs a source of power to enhance the electrolyzer to produce hydrogen fuel. Both on-grid and off-grid are designed to produce at least 80% of the demand. The optimal on-grid system consists of a 4 kW solar panel, a 2 kW AC/CD converter, and the electricity grid with LCOE and NPC of 0.1184$/kWh and $8,049, respectively, with a renewable fraction of 42.5%. The optimal off-grid solar/fuel cell system hybrid consists of a 3 kW solar panel, 0.1 kW fuel cell generator, 1 kW electrolyzer, 1 kW AC/DC converter, and 5 kg hydrogen tank at a LCOE and NPC of 0.5261$/kWh and $16,587, respectively. The LCOE from this hybrid is around 250% the LCOE from the electricity grid. The optimal off-grid solar/wind/fuel cell system consists of 2 kW solar panel, 3 kW wind turbine, 0.1 kW fuel cell generator, 2 kW AC/DC converter, 4 kW electrolyzer, and 5 kg hydrogen tank stands at LCOE and NPC of 0.3418$/kWh and $11,435, respectively. This hybrid is more feasible with the LCOE becoming 127% of the electricity grid LCOE. Moreover, a decrease in fuel cell generators' capital cost was done to observe the impact it might make on the total hybrid system. A decrease from 2400$/kW to 1800$/kW made the fuel cell system more appealing financially and replace wind turbines. The system consisted of a 2 kW solar panel, 0.3 kW fuel cell generator, 1 kW electrolyzer, 1 kW converter, and 5 kg hydrogen tank with an LCOE and NPC of 0.2918 $/kWh and $8,424, respectively. Also, a hypothetical case was introduced with the 2030 future costs of the renewable energy sources that are experimented. The results of this hypothesis insure that the decrease in price in certain renewables is effective only according to the location of the simulation. For METU NCC, a decrease in solar panel costs is much more effective than wind and fuel cell systems due to the high intensity of irradiation. Furthermore, another analysis is done for China with the same input parameters but different input resources. The optimal hybrid system for this case consists of 3.5 kW solar panel, two 1 kW wind turbines, 2 kW fuel cell generator, 2 kW AC/DC converter, 3 kW electrolyzer, and a 50 kg hydrogen tank. The LCOE is 0.7286 $/kWh and NPC is $35,326. The value of LCOE in China is 113% of the solar/wind/fuel cell system hybrid in Northern Cyprus and 385% of the grid's LCOE. Fuel cell systems are just not economically ready to be used in hybrid systems. Even when the capital cost of the fuel cell system dropped from 2400$/kW to 100$/kW, the solar/wind/fuel cell system hybrid system resulted in an LCOE (0.153$/kWh) higher than the common grid (0.150$/kWh).

Future Work

The main aim of this research is to infuse a new methodology in energy production and storage. Fuel cell systems are the future of renewable technology as they can be a part of production in the fuel cell generator, and storage in hydrogen fuel tanks. However, the price of fuel cells is still the barrier of its lack of use in hybrid systems or as a single unit. A future research can be to include fuel cells in larger projects and make use of economies of scale. Also, research must be made on whether or not fuel cell systems cooperate at efficiencies as their own, and if their efficiencies are somehow catalyzed by different renewable energy sources. Furthermore, if net metering and feed-in tariffs are to be included in the price calculations, the LCOE and NPV would be less than what they were in this thesis due to the advantage of selling back electricity to the grid. Nevertheless, the contribution of this thesis is to introduce a hybrid system that includes fuel cell systems that are not relatively common. However, there still needs to be a way for the prices of fuel cell systems to decrease drastically throughout the years for the thought of fuel cell systems to occur in hybrid systems.

Chapter 6 - References

[1] Green, J., & Newman, P. (2016). Disruptive innovation, stranded assets and forecasting: the rise and rise of renewable energy, 7(2), 169-187. Retrieved May 19, 2017.

[2] S. Nagl, M. Fürsch, C. Jägemann, and M. O. Bettzüge, “The economic value of storage in renewable power systems - the case of thermal energy storage in concentrating solar plants,” 2011.

[3] “World Bank Indicators,” 2016. [Online]. Available: http://data.worldbank.org/indicator/. [Accessed: 19-May-2017].

[4] A. Evans, V. Strezov, and T. J. Evans, “Assessment of sustainability indicators for renewable energy technologies,” Renew. Sustain. Energy Rev., vol. 13, no. 5, pp. 1082–1088, 2009.

[5] Olatomiwa, L., Mekhilef, S., Ismail, M. S., & Moghavvemi, M. (2016). Energy management strategies in hybrid renewable energy systems: A review, 62, 821-835. Retrieved June, 2017.

[6] Rose, A., Awang, M., Ahmad, F., Zamri, N., Afendee, M., & Deris, M. (2017). Achieving Efficient Decision Making Through Hybrid Reduction in Soft Set Theory , 7(3). Retrieved June, 2017.

[7] Root, T., Price, J., Hall, K., & Schneider, S. (2003). Nature. Fingerprints of global warming on wild animals and plants, 57-60. Retrieved June, 2017.

[8] Climate Change 2007: Working Group I: The Physical Science Basis. (2007). Retrieved June, 2017, from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch7s7-3.html

[9] Economic crisis effect on energy. (2009, May 25). Retrieved June, 2017, from https://www.iea.org/publications/freepublications/publication/impact.pdf

[10] "Consumption by fuel, 1965–2008". Statistical Review of World Energy 2009. BP. 8 June 2009. Retrieved June 2017.

[11] International Energy Outlook 2017. (2017). Retrieved June, 2017, from https://www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf

[12] EIA: Global oil market to rebalance during 2017-18. (2017, February 8). Retrieved June, 2017, from http://www.ogj.com/articles/2017/02/eia-global-oil-market-to-rebalance-during-2017-18.html

[13] Green, M. A. (1982). SciTech Connect. United States: Prentice-Hall, Inc., Englewood Cliffs, NJ. doi:6051511

[14] Meyers, G. (2014, December 31). Photovoltaic Dreaming 1875–1905: First Attempts At Commercializing PV. Retrieved June, 2017, from https://cleantechnica.com/2014/12/31/photovoltaic-dreaming-first-attempts-commercializing-pv/

[15] Baker, A. (2016, June 13). A History of Solar Cells: How Technology Has Evolved. Retrieved June, 2017, from https://www.solarpowerauthority.com/a-history-of-solar-cells/

[16] U.S. Department of Energy. (n.d.). Energy Efficiency and Renewable Energy, The History of Solar. Retrieved June, 2017, from https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

[17] McEvoy, A., Markvart, T., & Castañer, L. (2013). *Solar Cells Materials, Manufacture, and Operation* (2nd ed.).

[18] Electrical Technology. (2015, June 21). How to Make a Simple Solar Cell? Working of Photovoltaic Cells. Retrieved June, 2017, from https://www.electricaltechnology.org/2015/06/how-to-make-a-solar-cell-photovoltaic-cell.html

[19] Synergy Enviro Engineers. (n.d.). Solar Photovoltaic Energy. Retrieved June, 2017, from http://www.synergyenviron.com/resources/solar-photovoltaic-energy

[20] Malaysie Building Integrated Photovoltaic- Project (MBIPV) (2009), PV Industry
Handbook, Malaysian Industrial Development Authority.

[21] What are the different types of solar photovoltaic cells? (n.d.). Retrieved June, 2017, from https://www.renewableenergyhub.co.uk/solar-panels/what-are-the-different-types-of-solar-photovoltaic-cells.html

[22] Wind Energy Foundation. (n.d.). HISTORY OF WIND ENERGY. Retrieved June, 2017, from http://windenergyfoundation.org/about-wind-energy/history/

[23] Shahan, Z. (2014, November 21). History of Wind Turbines. Retrieved June, 2017, from http://www.renewableenergyworld.com/ugc/articles/2014/11/history-of-wind-turbines.html

[24] Wind Explained: History of Wind Power. (2017, May 24). Retrieved June, 2017, from https://www.eia.gov/energyexplained/index.cfm?page=wind_history

[25] Green M. A., Emery K., Hishikawa Y., Warta W., and Dunlop E. D. (2014) Solar cell efficiency tables (Version 45), Prog. Photovolt: Res. Appl., 23, 1–9, doi: 10.1002/pip.2573.

[26] Chiras, D. (2010). Wind Power Basics: A Green Energy Guide.

[27] Energy, Mines, and Resources. (2015, July 20). Retrieved June, 2017, from http://www.esc.gov.yk.ca/wind.html

[28] Global Wind Report Annual Market Update . (2011). Retrieved June, 2017, from http://gwec.net/wp-content/uploads/2012/06/Annual_report_2011_lowres.pdf

[29] F. Blaabjerg, Z. Chen, S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems", IEEE Trans. Power Electron., vol. 19, no. 5, pp. 1184-1194, Sep. 2004.

[30] J. G. Slootweg, W. L. Kling, "Is The Answer Blowing In The Wind?", IEEE Power & Energy Magazine, vol. 1, pp. 26-33, Nov.-Dec. 2003.

[31] Electricity from the wind – how turbines work. (2016, August 9). Retrieved June, 2017, from http://www.gogreengrid.com/2016/08/09/electricity-from-the-wind-how-turbines-work/

[32] Vertical Axis Wind Turbine. (2013). Retrieved June, 2017, from https://www.quietrevolution.com/

[33] Segura, F., & Andujar, J. M. (2009). Renewable and Sustainable Energy Reviews. *Fuel cells: History and updating. A walk along two centuries, 13*(9),

2309-2322. Retrieved July, 2017, from
http://www.sciencedirect.com/science/article/pii/S1364032109001336

[34] Carrette, L., Friedrich, K. A. and Stimming, U. (2001), Fuel Cells – Fundamentals and Applications. Fuel Cells, 1: 5–39. doi:10.1002/1615-6854(200105)1:1<5::AID-FUCE5>3.0.CO;2-G

[35] HYDROGEN FUEL News and Information about Hydrogen Fuel Cell and Electric Storage Technologies. (2017). Retrieved July, 2017, from http://www.alternative-energy-news.info/technology/hydrogen-fuel/

[36]] J.M. Andújar, F. Segura (2009). *Fuel cells: History and updating. A walk along two centuries* Available at: http://www.sciencedirect.com/science/article/pii/S1364032109001336

[37] Marccaci, S. (2015, January 26). 7 Interesting Global Renewable Energy Trends From NREL. Retrieved July, 2017, from https://cleantechnica.com/2015/01/26/7-interesting-global-renewable-energy-trends-from-nrel-charts-galore/

[38] Carrette, L., Friedrich, K., & Stimming, U. (december 15th 2000). Fuel Cells: Principles, Types, Fuels, and Applications, 1(4), 162-193. Retrieved July, 2017, from http://onlinelibrary.wiley.com/doi/10.1002/1439-7641(20001215)1:4%3C162::AID-CPHC162%3E3.0.CO;2-Z/full

[39] What Are Batteries, Fuel Cells, and Supercapacitors?
Martin Winter and Ralph J. Brodd*
Chemical Reviews 2004 104 (10), 4245-4270
DOI: 10.1021/cr020730k

[40] J. K. Kaldellis, D. Zafirakis, E. L. Kaldelli, and K. Kavadias, "Cost benefit analysis of a photovoltaic-energy storage electrification solution for remote islands," Renew. Energy, vol. 34, no. 5, 2009.

[41] C. Harris, J. P. Meyers, and M. E. Webber, "A unit commitment study of the application of energy storage toward the integration of renewable generation," J. Renew. Sustain. Energy, vol. 4, 2012.

[42] P. Denholm, E. Ela, B. Kirby, and M. Milligan, "The role of energy storage with renewable electricity generation", 2010.

[43] T. Ma, H. Yang, and L. Lu, "A feasibility study of a stand-alone hybrid solar-wind-battery system for a remote island," Appl. Energy, vol. 121, 2014.

[44] S. M. Hasnain, "Review on sustainable thermal energy storage technologies, Part II: cool thermal storage," Energy Convers. Manag., vol. 39, 1998.

[45] J. Paska, P. Biczel, and M. Kłos, "Hybrid power systems – An effective way of utilising primary energy sources," Renew. Energy, vol. 34, 2009.

[46] C. Koroneos, M. Michailidis, and N. Moussiopoulos, "Multi-objective optimization in energy systems: The case study of Lesvos Island, Greece," Renew. Sustain. Energy Rev., vol. 8, no. 1, pp. 91–100, 2004.

[47] HOMER SOFTWARE. (n.d.). Retrieved July, 2017, from https://www.homerenergy.com/HOMER_pro.html

[48] Bekele, G., & Palm, B. (2010). *Feasibility study for a standalone solar-wind-based hybrid energy system for application in Ethiopia, 87*(2). Retrieved July,

2017, from
http://www.sciencedirect.com/science/article/pii/S0306261909002451

[49] Bekele, G., & Tadesse, G. (2012). *Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia, 97*. Retrieved July, 2017, from https://www.deepdyve.com/lp/elsevier/feasibility-study-of-small-hydro-pv-wind-hybrid-system-for-off-grid-HSnHYpaA59.

[50] Mohammed, O., Amirat, Y., Binbouzid, M., & Elbast, A. (2014). *Optimal Design of a PV/Fuel Cell Hybrid Power System for the City of Brest in France*, 119-123. Retrieved July, 2017, from https://hal.archives-ouvertes.fr/hal-01023490/document.

[51] Kalinci, Hepbasli,, Y., & Dincer, A. (2015). Techno-Economic Analysis of a Stand-Alone Hybrid Renewable Energy System with Hydrogen Production and Storage Options. *International Journal of Hydrogen Energy, 40*, 7652-7654. Retrieved July, 2017.

[52] Khan, & Iqbal. (2005). Pre-feasibility Study of Stand-alone Hybrid Energy Systems for Applications in Newfoundland. *Renewable Energy, 30*, 835-854. Retrieved July, 2017.

[53] Mahlia, & Chan. (2011). Renewable and Sustainable Energy Reviews,. *Life Cycle Cost Analysis of Fuel Cell Based Cogeneration System for Residential Application in Malaysia*, *15*, 416-426. Retrieved July, 2017.

[54] Lonchar, J. (2017). The Analysis of Solar - Fuel Cell Hybrid Systems . *Thesis Statement* . Retrieved July, 2017, from

https://repository.asu.edu/attachments/186228/content/Lonchar_asu_0010N_16747.pdf.

[55] W. Pathirana and A. Muhtaroğlu, "*Multifaceted feasibility analysis of pv solar application in northern cyprus*," vol. 3, no. 4, 2013.

[56] M. Tariq, "*Methodology to size large scale solar pv installations for institutions with unidirectional metering*" Middle East Technical University, Northern Cyprus Campus, 2014.

[57] Meteotest Co., "Meteonorm Software," (2015)
Retrieved July 2017 from: http://meteonorm.com/.

[58] M. Yenen, "Modeling electrical energy production in northwestern cyprus based on solar and wind measurements," Middle East Technical University, Northern Cyprus Campus, 2015.

[59] S. Sadati, E. Jahani, and O. Taylan, "Technical and economic analyses for sizing PV power plant with storage system for METU NCC,", 2015.

[60] Vokas, G., Christandonis, N., & Skittides, F. (2005). Solar Energy. Hybrid photovoltaic–thermal systems for domestic heating and cooling—A theoretical approach, 607-615. Retrieved September, 2017, from https://ac.els-cdn.com/S0038092X05001349/1-s2.0-S0038092X05001349-main.pdf?_tid=ddc3d444-b330-11e7-8041-00000aab0f6b&acdnat=1508240992_bf3a76dc0b419e743659f4b8eed824b4.

[61] Sinha, S., & Chandel, S. S. (2014). Renewable and Sustainable Energy Reviews. Review of software tools for hybrid renewable energy systems, 192-205.

Retrieved September, 2017, from https://ac.els-cdn.com/S136403211400046X/1-s2.0-S136403211400046X-main.pdf?_tid=790bcd70-b337-11e7-9d70-00000aab0f02&acdnat=1508243829_ff379a4b72723ed95d8709ad1d49478f.

[62] Hernández-Moro , J., & Martínez-Duart, J. (2013). Renew. Sustain. Energy Rev. Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution, 20, 119-132. Retrieved September, 2017.

[63] Ö. Muhtaroglu, “State planning organization,” N. Cyprus Economic Planning Department, 2012.

[64] “SolarGIS,” 2016. [Online]. Available: http://solargis.com/products/maps-and gis-data. [Accessed: Sep-2017].

[65] Ali, S., Zuberi, M., & Baker, D. (2015). A study to incorporate renewable energy technologies into the power portfolio of Karachi, Pakistan, 47, 14-22. Retrieved September, 2017.

[66] Riberio, A., Arouca, M., & Coelho, D. (2016). Renewable Energy. Electric energy generation from small-scale solar and wind power in Brazil: The influence of location, area and shape, 85, 554-563. Retrieved September, 2017, from http://www.sciencedirect.com/science/article/pii/S0960148115300938

[67] O'Hayre, R., Cha, S. W., & Prinz, F. (2016). Fuel Cell Fundamentals. USA.

[68] “SolarGIS,” 2016. [Online]. Available: http://solargis.com/products/maps-and gis-data. [Accessed: Sept-2017].

[69] EnergySage. (2017). What Are The Best Solar Panels on the Market? The Complete Ranking. Retrieved October, 2017, from http://news.energysage.com/best-solar-panels-complete-ranking/

[70] Solyali, D., Tolun, S., Aslan, Z., & Altunc, M. (2016). Renew. Sustain. Energy Rev. Wind resource assessment of Northern Cyprus, 55, 180-187. Retrieved November, 2017.

[71] Geuss, M. (2017, October 13). Solar now costs 6¢ per kilowatt-hour, beating government goal by 3 years. Retrieved November, 2017, from https://arstechnica.com/science/2017/09/solar-now-costs-6-per-kilowatt-hour-beating-government-goal-by-3-years/

[72] Strategies to reach 30 GW of "behind-the-meter" wind generation by 2030. (2015, March). Retrieved November, 2017, from http://distributedwind.org/wp-content/uploads/2012/08/DWEA-Distributed-Wind-Vision.pdf

[73] Stafell, I., & Green, R. (2016). The cost of domestic fuel cell micro-CHP systems. Retrieved November, 2017, from https://spiral.imperial.ac.uk/bitstream/10044/1/9844/2/The%20cost%20of%20domestic%20fuel%20cell%20micro-CHP%20systems%20(ICBS%20format).pdf.

[74] The Social Cost of Carbon Estimating the Benefits of Reducing Greenhouse Gas Emissions. (2017, January 19). Retrieved November, 2017, from https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html