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ANALYSIS OF GREEN HYDROGEN PRODUCTION USING SOLAR DISH STIRLING SYSTEM IN ANKARA REGION

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
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FREDERICK CAN TROSTER

A MASTER OF SCIENCE
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A THESIS SUBMITTED TO
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FREDERICK CAN TROSTER

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
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IN
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Approval of the Graduate School of Natural and Applied Sciences, Atilim University

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Prof. Dr. Ender Keskinkılıç
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I certify that this thesis satisfies all the requirements as a thesis for the degree of **Master of Science in Mechanical Engineering Department, Atilim University**.

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ABSTRACT

ANALYSIS OF GREEN HYDROGEN PRODUCTION USING SOLAR DISH STIRLING SYSTEM IN ANKARA REGION

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The world's energy demand is growing in parallel with the world's population and economy. In today's world, fossil fuels provide most of the electricity. By damaging the environment, the usage of fossil fuels endangers our future. Renewable energy sources are becoming more popular as technology advances. These eco-friendly supplies are critical for our future. Renewable energy is defined as energy derived from natural sources such as solar, wind, and geothermal. The sun is the most basic source of energy. Many systems have been developed to generate energy from the sun. Concentrated solar energy systems are becoming increasingly popular for generating solar energy. One of the concentrated systems, Solar Dish Stirling technology, attracts attention due to its great efficiency. This system, consisting of a dish with a mirror, a receiver, and a motor, can convert solar energy to electrical energy with 32% efficiency.

Energy storage, in addition to energy generation, is critical for our future. One of the energy storage strategies, hydrogen production, looks promising for the future. The energy source used in hydrogen production is categorized. Green hydrogen is hydrogen produced using ecologically friendly, renewable energy sources. This zero-emission manufacturing approach is increasing in popularity. An electrolyzer is used in the generation of hydrogen. The water is split into hydrogen and oxygen by the electrolyzer. The separated hydrogen can be compressed with the help of a compressor and stored for later use.

Green hydrogen production simulation in the Ankara region was investigated in this study using Solar Dish Stirling, one of the concentrated solar energy technologies. Solar Dish Stirling, PEM water electrolyzer, hydrogen compressor, and hydrogen tank for storage are all part of the system. The electrolyzer was powered by electricity generated by the Ripasso dish Stirling system. The offsetting approach has been implemented in the system. When there is insufficient radiation, but the total daily electricity generation is sufficient to run the electrolyzer, the electrolyzer and compressor are activated, and hydrogen production begins. The system can create more electricity and hydrogen in the summer than in the winter.

The LCOE value was found 0.4595 $/kWh and compared to international values. Following the offset, strategy provides an advantage for the cost of the system. The system has a capacity of 47950 kW/h per year and can produce 377 kilograms of hydrogen per year. These systems are critical for our future. It will be a good solution to environmental challenges with growing technology and reduced investment costs.

Keywords: Green Hydrogen Production, Solar Dish Stirling, Electrolysis, Hydrogen Storage.

ÖZ

ANKARA BÖLGESİNDE GÜNEŞ PARABOLİK ÇANAK TEKNOLOJİSİ İLE YEŞİL HİDROJEN ÜRETİMİNİN ANALİZİ

Troster, Frederick
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JANUARY 2023, 55 Sayfa

Artan dünya nüfusu ve büyüyen ekonomiler ile dünya enerji ihtiyacı artmaktadır. Günümüz dünyasında üretilen elektrik çoğunlukla fosil yakıtlardan karşılanmaktadır. Fosil yakıtların kullanımı çevreyi kirleterek geleceğimizi tehlikeye atmaktadır. Gelişen teknoloji ile yenilenebilir enerji kaynaklarının popülerliği artmaktadır. Çevre dostu olan bu kaynaklar geleceğimiz için önem arz etmektedir. Yenilenebilir enerji kaynakları, güneş, rüzgâr, jeotermal gibi doğal kaynaklardan elde edilebilen enerji olarak ayrılır. Güneş en temel enerji kaynağıdır. Güneşten elektrik elde etmek için birçok sistem geliştirilmiştir. Konsantre güneş enerji sistemleri güneşten elektrik üretme noktasında popülerliği giderek artmaktadır. Konsantre sistemlerden solar güneş parabolik çanak teknolojisi, konsantre sistemler arasındaki yüksek verimliliği ile dikkatleri üstüne çeker. Ayna ile kaplanmış bir çanak, bir alıcı ve bir motor ile çalışan bu sistem güneş enerjisini elektrik enerjisine %32 verimlilikle sağlayabilmektedir.

Enerji üretiminin yanı sıra enerji depolanması konusunda geleceğimiz için önem arz etmektedir. Enerji depolama stratejilerinden biri olan hidrojen üretimi gelecek için umut vadetmektedir. Hidrojen üretimi, kullandığı enerji kaynağına göre sınıflandırır. Çevre dostu, yenilenebilir enerji kaynaklarıyla üretilen hidrojene yeşil hidrojen denir. sıfır emisyon değerine sahip bu üretim şekli popülerliği giderek artmaktadır. Hidrojen üretimi elektrolizör yardımıyla gerçekleşir. Elektrolizör cihazı suyu hidrojen ve oksijen olarak ayrıştırır. Ayrılan hidrojen kompresör yardımıyla sıkıştırılarak kullanım için depolanabilir.

Bu çalışmada konsantre güneş enerjisi teknolojilerinden solar parabolik çanak ile Ankara bölgesinde yeşil hidrojen üretimi modellemesi yapılıştır. Oluşturulan sistemde parabolik çanak, 4480W gücünde PEM elektrolizör, hidrojen kompresörü ve depolama için hidrojen tankı bulunmaktadır. Ripasso parabolic çanak sistemi baz alınarak elektrik üretimi ile elektrolizör çalıştırılmıştır. Sistem mahsuplaşma stratejisini benimsemiştir. Yeterli güneş radyasyonu sağlandığında sistemde üretilen toplam günlük elektrik üretimi elektrolizör çalışma gücünü sağladığında elektrolizör ve kompresör devreye girerek hidrojen üretimi başlamaktadır. Yaz aylarında sitemin kış aylarına göre daha çok elektrik ve hidrojen üretebildiği tespit edilmiştir.

LCOE değeri 0.4595 $/kWh olarak bulunmuş ve uluslararası değerlerle karşılaştırılmıştır. Sistem yıllık 47950 kW/h üretime sahip olup yılda 377 kilogram hidrojen üretebilmektedir. Sistemin mahsuplaşma stratejisi izlemesi avantaj sağlamaktadır. Bu sistemler geleceğimiz için önemlidir. Gelişen teknoloji ve yatırım maliyetlerinin düşmesiyle, çevre sorunlarına iyi bir çözüm olacaktır.

Anahtar Kelimeler: Yeşil Hidrojen Üretimi, Parabolik Çanak, Elektroliz, Hidrojen Depolama

To my family

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

CSP : Concentrated Solar Power

DNI : Direct Normal Irradiance

PTC : Parabolic Trough Collector

LFR : Linear Fresnel Reflector

SPT : Solar Power Tower

PDC : Parabolic Dish Collector

E : Solar Insolation

η : Efficiency

A_{mirr} : Mirror Area

PSE : Power of Stirling Dish

η_{conc} : Concentrator efficiency

η_{rec} : Receiver Efficiency

η_{S} : Stirling Efficiency

η_{EG} : Electric generator Efficiency

D : Diameter of dish

Π : Pi number

ρ : Clean mirror reflectance

α : Effective cavity receiver absorptance

γ : Intercept factor of the collector

η_{cycle} : Mirror cleanliness factor

η_{0} : Optical efficiency

ε : Effective emissivity of the cavity receiver

σ : Stefan–Boltzmann constant

h_r : Effective convective coefficient of the cavity receiver

A_r : The surface area of the aperture of the receiver

T_r : Receiver temperature

T_{air} : External Ambient Temperature

T_{sky} : Effective sky temperature

W : Watt

CO_2 : Carbon-dioxide

H_2 : Hydrogen

V_{cell} : Cell voltage

n_{cell} : Number of cells in electrolyzer

V_{stack} : Electrolyzer stack voltage

F : Faraday’s constant

P : Pressure

n : Mole

R : Gas constant

T : Temperature

a : The net intermolecular attractive

b : The finite volume of molecules

LCOE : Levelized Cost of Electricity

i : Interest rate

f : Aannual infilation

i_0 : Nominal interest rate

CRF : Capital Recovery Cost

$E_{(t)}$: Electricity production kWh

$I_{(t)}$: Investment cost

$M_{(t)}$: Operation & Maintenance cost

P_{comp} : Power of the compressor

T_1 : Compresor inlet temperature

T_2 : Compresor outlet temperature

M : Hydrogen molecular weight

Q_m : Flow rate of the hydrogen

k : Isentropic coefficient of hydrogen

E_{CO_2} : Emissions of CO_2 (metric tons/yr)

FSR : Fuel and feedstock supply rate (kg/day)

CF : Carbon fraction in feedstock (kg C/kg feed stock)

S : Carbon fraction diverted and accounted for elsewhere (kg C/day)

COF : Carbon oxidation factor of feedstock

CHAPTER 1

1. INTRODUCTION

1.1. PROBLEM STATEMENT

The world's energy demand is increasing because of rising population and economic growth. The main demand for this energy is supplied by fossil fuels. These fossil fuels threaten our future by harming the environment. As a solution to this challenge, renewable energy sources are becoming a key for the future and more popular day by day. Renewable energy systems are environmentally friendly and promising for our future. However, because these systems rely on natural resources such as the sun and wind, a hybridization or storage approach for sustainability has been followed. Today, energy storage plays a critical role in our lives. One of the forms of energy storage is hydrogen storage. Hydrogen is one of the most abundant basic elements in nature. The most environmentally friendly way of hydrogen production, also known as green hydrogen production, is important for our future world. The electrolyzer devices used for green hydrogen production are powered by electricity generated by renewable energy sources, and hydrogen production is given. These systems should be increased for the world of our future.

1.2. PURPOSE OF STUDY

The purpose of this study is to produce green hydrogen with solar dish stirling, which is one of the concentrated solar energy systems from renewable energy sources. Hydrogen production is critical to energy storage. This operation must be carried out in an environmentally friendly manner to protect our future world. Green hydrogen generation is the creation of hydrogen from the splitting of water using an electrolyzer in which the energy is supplied from renewable energy sources provides zero emissions. As a result, this method is environmentally friendly and promising for our future.

Solar energy is the most basic energy form in our universe and electricity can be produced from the sun with many different technologies. Solar dish stirling, which is one of the developing concentrated solar energy systems, draws attention with its high concentration and efficiency value among the concentrated systems, but it has remained in the background due to its investment cost. Analysis of the solar dish stirling and electrolyzer system was performed in the Ankara region.

1.3. AIMS AND OBJECTIVE

This study aims to draw attention to the possibility of producing green hydrogen with the solar dish stirling system, one of the most efficient concentrated solar energy systems. Green hydrogen production is an important strategy and method for energy storage. Hydrogen produced with electricity from renewable sources is called green hydrogen. Being environmentally friendly, this technology is an important solution in terms of environmental pollution and sustainability. Green hydrogen generation using solar dish stirling electricity is extremely valuable for our future. With its high efficiency rate, solar dish stirling technology is gaining prominence among concentrated systems. The sun is our world's most basic energy source, and hydrogen is one of its most abundant elements. The two most fundamental resources can be used to create a more sustainable future.

CHAPTER 2

2. LITERATURE SURVEY

2.1. RENEWABLE ENERGY

The need for energy is gradually increasing because of the rising population and developing economies. Most of today's energy demand is still satisfied by fossil fuels. Fossil fuel-based energy sources create environmental concerns such as global warming [1]. The burning of fossil fuels is recognized to generate direct pollution, resulting in greenhouse gas emissions which are damaging the environment and cause a decline in sustainable development [2].

World demand can be met by environmentally friendly renewable energy sources. Renewable energy systems with environmentally favorable qualities and no emission value are gaining popularity as society's understanding of the need for a clean environment grow [3].

Renewable energy is an alternative to traditional energy, which is based on natural sources. There are numerous ways to contribute to environmental improvement by selecting a greener energy option. Renewable energy enables users to select green energy solutions that lower their carbon impact. Renewable power is rising, as innovation cuts down costs and starts to deliver on the promise of a clean energy future. These systems will be critical in decarbonizing our energy systems in the future decades [4].

Renewables have emerged as a strategic choice in energy consumption and have been assigned a critical position in the global energy mix in the long run. It can meet the rising demand for energy consumption, as well as the commitment to reduce environmental pressures caused by energy consumption and attain energy independence [5]. According to values obtained from the International Energy Agency, a total of 7900 TWh generation is gathered by renewable systems in 2021 and by 2026 it is predicted to exceed 11,300 TWh [6].

Renewable energy sources generate 28% of global power production. Hydroelectric power plants, wind farms, and solar power plants make up the vast bulk of this production [7].

Hydropower is a form of energy obtained from flowing water. Flowing water provides energy that may be harnessed and transformed into power by employing turbines. Dams are the most frequent type of hydropower, while other versions that harvest wave and tidal power are becoming increasingly widespread. The largest power plants are based in Itaipu, Brazil with a capacity of 14,000 MW, and Three Gorges in China 22,400 MW [8].

Biomass is a type of renewable energy source that could generate both heat and electricity through thermochemical and biochemical conversion processes. It comprises both energy crops and wastes, such as forestry leftovers and a variety of other agricultural and industrial byproducts, to generate electricity. The primary step in a biomass power plant for producing steam is fuel combustion. Steam can be used to power industrial activities or to generate energy [9].

Wind energy is one of the increasingly popular renewable energy sources. Wind energy can be converted to mechanical than to electricity by wind turbines. They are grouped according to their installation area offshore and onshore and as in the type of turbine horizontal and vertical. Horizontal axis wind turbines have the primary rotor shaft running horizontally and the generator at the top of a tower, both of which must be aimed towards the wind in some way. Many of these turbines also offer independent blade pitch control, which means that each of the turbine's blades may be pitched around its longitudinal axis independently. Vertical-axis wind turbines have a higher potential to produce more than horizontal turbines. There are two different designs called Savonius and Darrieus. Svonius works with the principle of drag force and Darrieus uses the lift force. The advantage of the vertical design is that could operate independently of the wind direction [10].

Geothermal power plants can use geothermal heat to generate energy or feed it into district heating systems. Temperatures in the Earth's interior range between 3000 °C and 10000 °C. Radioactive decay generates enough energy to cause such temperatures. Temperature variations between the Earth's core and crust produce a constant heat flow [11].

The sun is the universe's primary energy source. There are numerous technologies available to transform this energy into electricity. Photovoltaic panels are one type of technology. By absorbing sunlight, this technology converts light energy to electrical current. Concentrated solar power is another method of turning solar energy into electricity. Reflecting solar radiation into a tiny area using lenses and mirrors to generate heat or power. According to Our World in data [7] in 2022, electricity production of solar energy is 1032.50 terawatts which are 3% of the world’s electricity.

Turkey has an important solar energy potential due to its geographical location. According to the Turkey Solar Energy Potential Atlas (GEPA), the average annual total sunshine duration is 2741 hours, and the average annual total radiation value is calculated as 1527.46 kWh/m^2. At the end of June 2022, solar-based electricity installed power is 8479 MW, and its ratio to the total installed power is 8.35% [12].

Hydrogen is one of the most abundant elements in nature. It is a great energy carrier kind of way of energy storage. It can be kept as a fuel and utilized in transportation, fuel cells, internal combustion engines, or turbines. Stored 1 kg of hydrogen has the potential of supplying 33.33 kWh [13]. The most common way of producing hydrogen is by steam reforming. Since the energy required for this approach is derived from fossil fuel sources, it is unsuitable for our environment, and it is categorized as grey hydrogen because of its emission level. On the other, there is an environmentally friendly method to produce hydrogen which is called electrolysis. Electrolysis is a technique that splits water into hydrogen and oxygen by a device called an electrolyzer. When the energy required for this technique is obtained from renewable sources, it is referred to as green hydrogen.

2.2.GREEN HYDROGEN PRODUCTION

Hydrogen is found in many substances. The most abundant is water. Also, hydrogen can be produced from hydrocarbons, biomass hydrogen sulfide. Henry Cavendish discovered a lightweight gas that, when burnt in air, converted into the water in 1766. In 1787, Antoine Lavoisier called this new gas "hydrogen" [14].

Grey hydrogen is seen as a polluting form of hydrogen. In contrast to grey hydrogen, blue hydrogen defines carbon capture and storage. When a renewable energy source is used for hydrogen generation is referred to as green hydrogen. As a result, green hydrogen is recognized as a clean (low-carbon-emissions) form of hydrogen energy [15].

Steam reforming hydrogen also known as conventional or grey H_2 is the most often used method for producing hydrogen. Methane, ethane, methanol, ethanol, acetone, and higher hydrocarbons could be also used. Steam reforming is currently reliant on fossil resources and is associated with significant process-related CO_2 emissions. With current yearly emissions of around 530 Mt/a, this process significantly contributes to climate change [16].

Blue hydrogen is produced by reforming steam methane using traditional CO_2 collection methods. CO_2 capture adds significant costs to blue hydrogen, and large-scale infrastructure for CO_2 transport and storage is not yet generally available. Furthermore, CO_2 extraction using traditional technology is insufficient, meaning that blue hydrogen still emits considerable amounts of CO_2 [17].

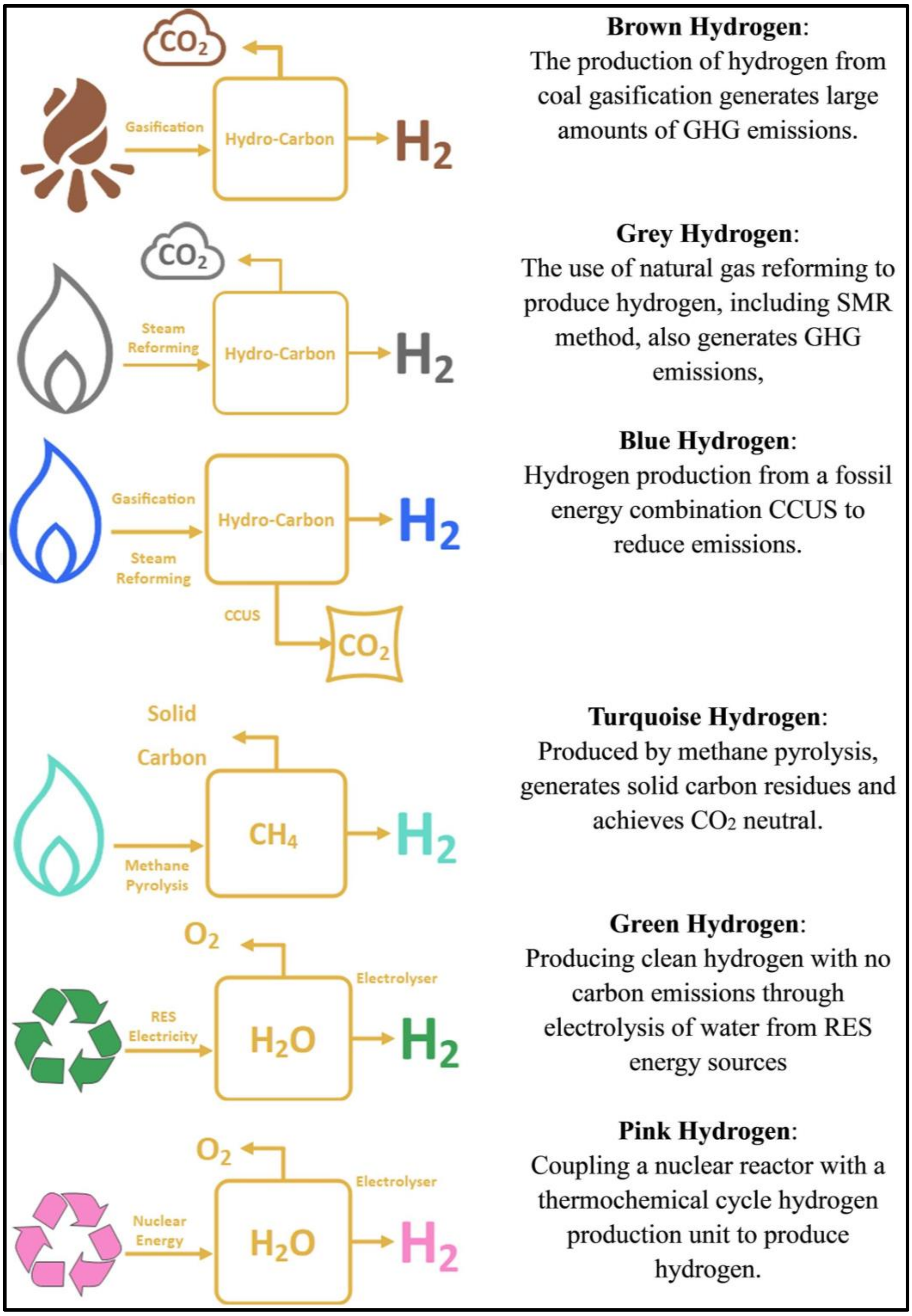
There should be no greenhouse gas or carbon dioxide emissions during the production of green hydrogen. The types of energy required to extract hydrogen from a substance can be divided into four categories: thermal, electrical, photonic, and biological. electrical energy is supplied by renewable sources such as solar, wind, and geothermal tidal.

There are many ways of green hydrogen production. One method for producing hydrogen from methane is plasma arc decomposition. In this process, methane can be decomposed under thermal plasma with no carbon dioxide release. Producing hydrogen with heat from the water is called water thermolysis. Which requires high-temperature resources above 2500 K. The challenging part of this method is the separation of hydrogen and oxygen, to avoid becoming explosive. It is possible to create hydrogen from hydrogen sulfide, which is abundant in nature. To obtain hydrogen from hydrogen sulfide thermos catalytic cracking method is used. This reaction creates two products hydrogen and sulfur also there are thermochemical cycles for splitting hydrogen sulfide. Artificial photosynthesis, Photocatalytic water splitting, and photoelectrochemical hydrogen production are the other methods of green hydrogen production [18].

One such emission-free method of electrochemical water splitting is water electrolysis, which uses electricity to produce green hydrogen. For the past 200 years, water electrolysis has been a well-known process for producing sustainable hydrogen. However, due to financial difficulties, only 4% of the hydrogen (65 million tons) needed for the world can be produced using water electrolysis [19].

Green hydrogen can be produced using geothermal energy. The generated power from low and high-temperature sources is then used to produce green hydrogen in alkaline and high-temperature solid oxide electrolyzers [20].

A system analysis is made, investigating three grid-connected plants with the same capacities of 100 MW. These three configurations' purpose is to produce green hydrogen from renewable sources such as wind and solar. The first system is a hybrid system that consists of the PV system and wind turbines with 50 MW capacities each. The second is considered as only having a PV system and the last configuration consist of only wind turbines powering a 24 MW alkaline water electrolyzer. It is discovered how to choose acceptable and energy-reliable places to install hybrid or single PV-wind turbine systems, as well as compare hybrid and single PV-WT systems in the same area [21].



Brown Hydrogen:
The production of hydrogen from coal gasification generates large amounts of GHG emissions.

Grey Hydrogen:
The use of natural gas reforming to produce hydrogen, including SMR method, also generates GHG emissions,

Blue Hydrogen:
Hydrogen production from a fossil energy combination CCUS to reduce emissions.

Turquoise Hydrogen:
Produced by methane pyrolysis, generates solid carbon residues and achieves CO_2 neutral.

Green Hydrogen:
Producing clean hydrogen with no carbon emissions through electrolysis of water from RES energy sources

Pink Hydrogen:
Coupling a nuclear reactor with a thermochemical cycle hydrogen production unit to produce hydrogen.

Figure 2.1. Hydrogen production methods [22].

Figure 2.1 shows the classification of hydrogen production by source. As is seen, there are six categories according to main sources.

Hydrogen production frequently needs to be built on the electrical grid mix at the specific production site during a certain period rather than relying solely on locally mined renewable energy sources. Many hydrogen production technologies, like water electrolysis, work best when they are run continuously and for longer periods to remain financially competitive with traditional hydrogen generation [23].

2.2.1. SOLAR BASED GREEN HYDROGEN PRODUCTION

Energy generated directly from sunlight is a promising solution to meeting the requirement for clean energy while avoiding an ecological footprint. Without a doubt, hydrogen is the future fuel and an energy carrier. It contains no carbon and is thus environmentally friendly. Even though hydrogen is naturally found on Earth in both organic and inorganic molecules [24]. Green hydrogen production can be compared to photosynthesis that takes place in nature. Splitting water efficiently into usable hydrogen might become new industrial photosynthesis that would produce clean fuel with no waste [25]. To achieve this challenge economically few processes are developed which are represented in Table 2.1.

Table 2.1 Hydrogen production by solar energy[24].

Solar Hydrogen Production	**Processes**	**End Products**
PV	Water electrolysis	$H_2,0_2$
Photoelectrochemical	Photo electrolysis of water	H_2
Photobiological	Photo biolysis/Photo-synthesis	$H_2,0_2$
Concentrated Solar Thermal	Thermolysis-Thermal dissociation of water	$H_2,0_2$
	Thermochemical	$H_2,0_2$
	Electrolysis via electricity generation from solar thermal energy	$H_2,0_2$

The production of hydrogen from water electrolysis utilizing electricity generated by PV cells began in the early 1970s. The PV-based hydrogen generation is primarily associated with an electrolyzer unit that electrolyzes water into hydrogen and oxygen using the DC electricity generated by the PV panels. Looking at the result, solar energy converted to chemical energy, to hydrogen, is nearly 16%. A simple illustration of the process in shown in Figure 2.2 [24].

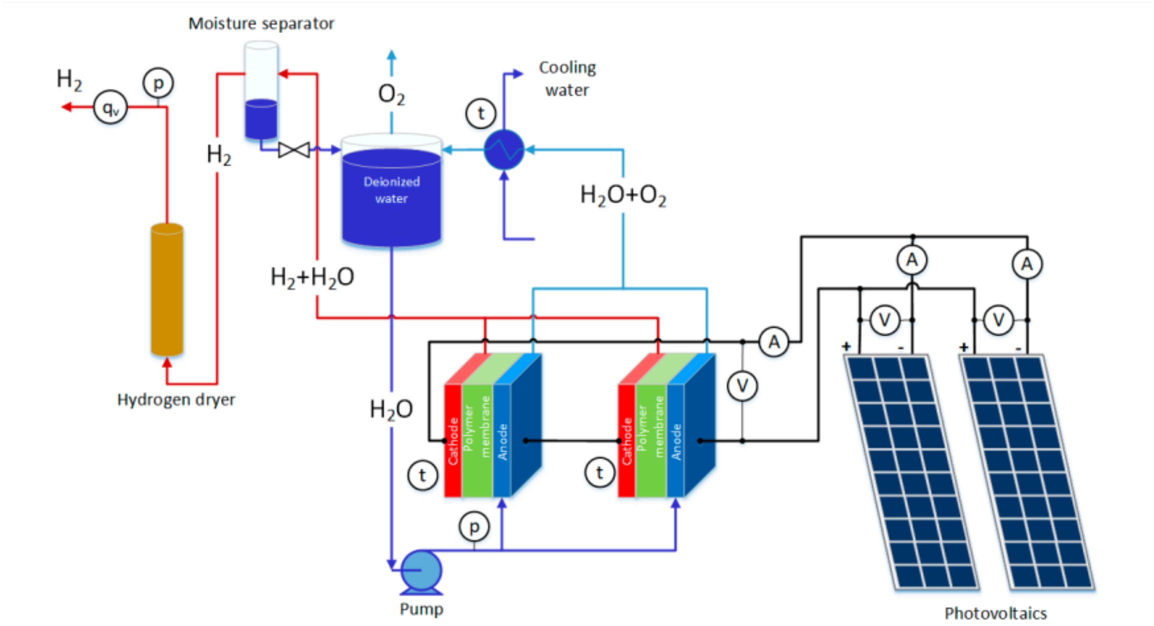


Figure 2.2. Schematic of a PV&Electrolyzer system [26].

Photocatalysis is a redox reaction that occurs when a catalyst absorbs photons to produce high-energy electrons and holes. Fujishima and Honda discovered in 1972 that photocatalytic water splitting can generate hydrogen on the TiO_2 electrode. This discovery lays the groundwork for solar water splitting to make hydrogen. Photocatalytic water splitting for hydrogen production involves the use of a semiconductor photocatalyst. This generates an electron-hole pair under solar irradiation. From the reduction reaction, desired product hydrogen can be obtained. This process can transform and store solar energy as chemical energy, making it a promising environmentally friendly green hydrogen manufacturing technology [27].

Photobiological hydrogen production has the same principles as plant and algae photosynthesis for hydrogen generation. Photosynthesis in plants and algae results in the splitting of water into oxygen and a reducing agent powerful enough to convert CO_2 or protons to carbohydrates or hydrogen, respectively. An effective biological converter, microalgae, and a photobioreactor are used in the photobiological generation of hydrogen from water. Biological approaches for solar hydrogen generation have not yet been established for commercial usage. Because trees and crops convert sunlight at efficiencies of less than 1%, this technology is still in the early stages of development [24].

Solar thermal-chemical cycles for hydrogen production are still in the development phase. The iron-oxide redox pair cycle has two stages for splitting water. Water is thermally decomposed in a high-temperature solar receiver reactor made comprised of a honeycomb ceramic support coated with metal oxide, which works as an active redox reagent. At 800 ^oC, the active redox material is oxidized by oxygen from the water molecules, releasing pure hydrogen. During the second stage, the fully oxidized reagent is regenerated by raising the temperature to around 1200 ^oC in an oxygen-free environment. The use of nitrogen as a flushing gas causes the release of absorbed oxygen. The technique is projected to reach more than 70% efficiency in terms of solar heat input. Within the HYDROSOL Project, a laboratory-scale solar iron-oxide-based redox system was designed, built, and tested [28].

A solar-powered hydrogen generation process is comprised of four major components: a concentrating collector, a heat engine, an electrical generator, and an electrolyzer. A heat storage unit can be added to the system to deliver the needed thermal energy of the heat engine continuously. While solar radiation is focused on the absorber connected to the heat engine, a portion of the absorbed energy is transformed into mechanical work and the remaining is dissipated. The mechanical energy is converted to electrical power using an electrical generator. The power created is then used to electrolyze water. A system is shown in Figure 2.3, this technique involves moving parts such as a generator and a heat engine, which needs more maintenance as compared to other hydrogen systems [29].

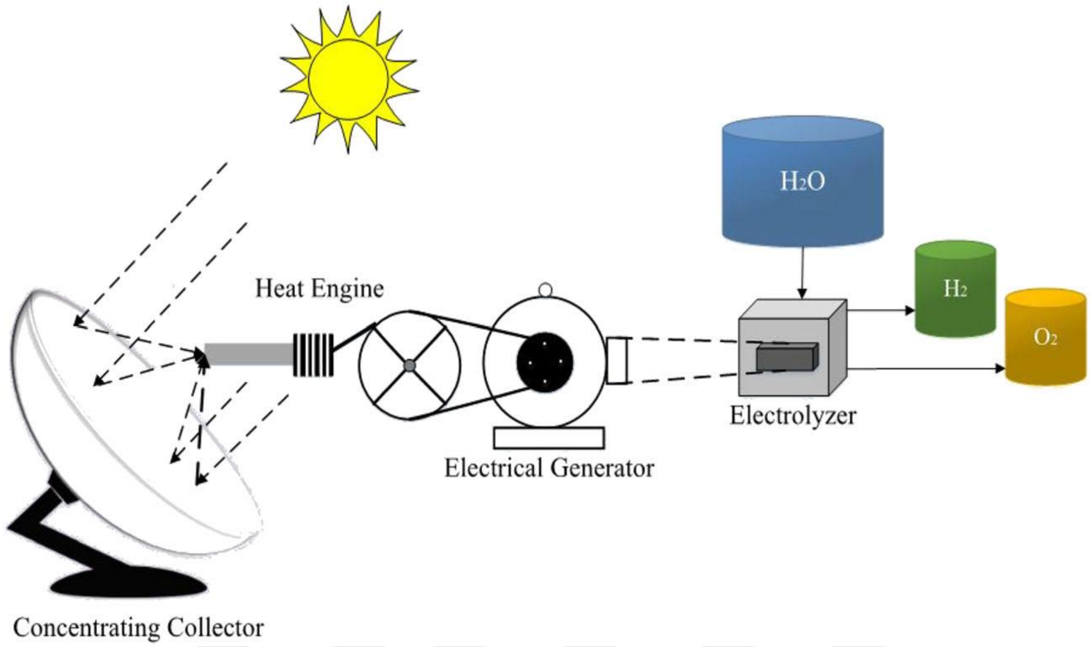


Figure 2.3. Concentrating collector hydrogen production [24].

2.2.2. PARABOLIC TROUGH COLLECTOR

Many parabolic trough collector systems have been built. They are in operation all over the world. Most of these systems supply steam to industry. As an energy source for creating steam, it is a way to replace fossil fuels. The solar field is made up of a series of parallel-connected reflectors with aperture areas ranging from 500 to 5000 m^2. However, most of these systems provide steam ranging from 150 to 200 ^oC. The collectors, pumps and power generation system are the main components of the systems. The collectors heat a synthetic heat transfer fluid, which is routed to the solar steam generator and superheater, where it provides the steam that drives the turbine [30].

Parabolic trough technology is the most developed of the solar thermal technologies due to substantial experience with the systems and the formation of a small commercial sector to manufacture and market these systems [31]. The system illustration is shown in Figure 2.4.

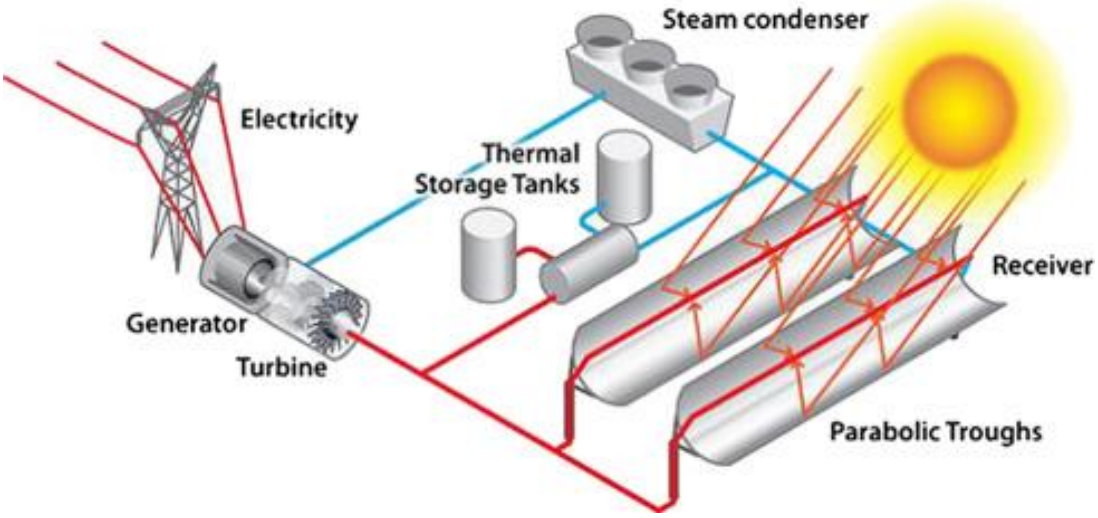


Figure 2.4. Parabolic trough system [32].

2.2.3. SOLAR POWER TOWER

Solar Tower technology utilizes a huge number of heliostats with dual-axis control. These heliostats reflect direct beam solar energy to a stationary receiver atop a tower. Heat transfer fluid absorbs heat in the receiver and transfers thermal energy to the power block to generate electricity [33]. In Figure 2.5 the working principle and the components of the system are shown.

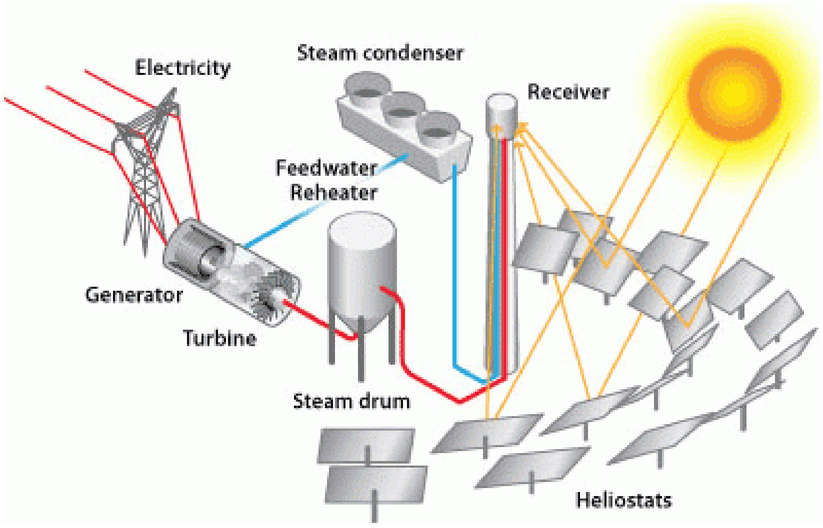


Figure 2.5. Solar tower system [34].

The first application of the system was made in 1978, in Mojave Desert, USA. The system was 1 MW. Nowadays there are Solar Tower Plants that can reach capacities of over 100 MW. Ashalim Power Station in Israel was completed in 2019 and has a capacity of 121 MW. Quarzazate Solar Power Station which is in Morocco with a capacity of 150 MW was completed in 2019 [35]. The biggest installed solar tower project is in the USA. Ivanpah Solar Facility has 3 towers with a capacity of 390 MW [36].

2.2.4. LINEAR FRESNEL REFLECTOR

Liner Fresnel reflector technology is one of the four basic concentrated solar power systems with the greatest potential for producing competitive electrical power from solar energy. Concentrated solar power currently produces less than 2% of solar electric capacity. However, when paired with thermal energy storage, linear Fresnel has an advantage in storing excess energy [37].

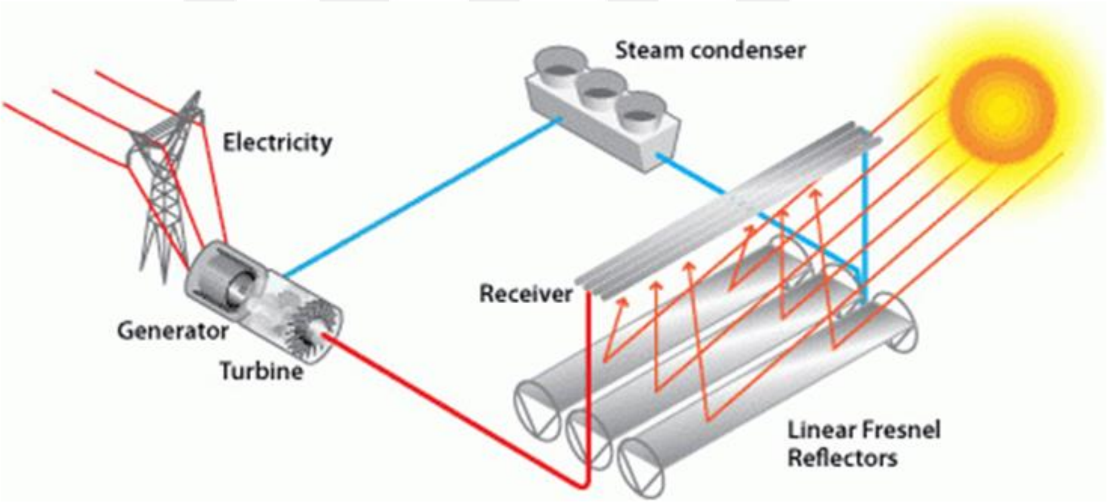


Figure 2.6. Linear Fresnel reflector system [38].

To reflect solar radiation to the linear receiver, the linear Fresnel uses rows of long, flat, or curved mirrors. The receiver is a permanent structure that is parallel to the linear reflectors and sits atop a tower. Reflectors that could follow the sun depending on a single or two axes tracking system. The system is shown in Figure 2.6. The main advantage of linear Fresnel systems is that they may generate direct steam without the use of working fluid or heat exchangers because of their basic structure, which includes flexibly bending mirrors and permanent receivers [30].

2.2.5. PARABOLIC DISH

Aside from power generation, the solar dish collector can be used for a variety of other purposes. The most advanced application is for generating power with Stirling engines. In terms of efficiency conversion, solar dish Stirling systems have demonstrated impressive outcomes; approximately 30% of the sunray could be collected and transformed into electricity [39]. These systems can reach up to 1500 ^{o}C [30].

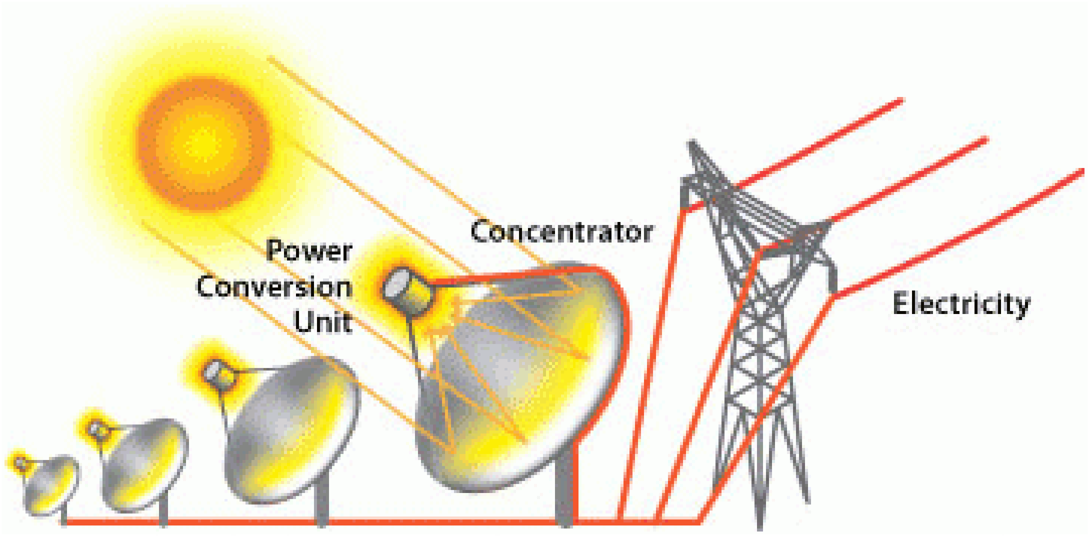


Figure 2.7. Parabolic dish collector [40]

The solar dish Stirling technology consists of a parabolic dish solar concentrator with a main structure, a receiver, and a Stirling engine which is shown in Figure 2.7. To maximize solar radiation, the Stirling engine and receiver are located at the dish's focal point. The major role of the thermal receiver is to guarantee that solar radiations are distributed uniformly at the Stirling engine. Stirling engines can be mounted with an alternator for electric power generation. Using a solar tracking device, the parabolic solar dishes are automatically aligned to the sun all day. Solar rays are continuously focused on the focal point of the parabolic dish concentrator, where the SE is installed [41].

2.2.6. SOLAR DISH STIRLING

In the 1980s, several solar dish Stirling systems were demonstrated in the United States, Spain, Japan, and a few other countries. In the early 2000s, some new dish Stirling systems were developed. This system has the highest conversion efficiency in the generation of electricity.

The collector system consists of two major components: a solar concentrator and a thermal receiver. The collector system aims to supply thermal energy to power the Stirling engine. The parabolic dish is used to focus solar radiation on the aperture of the receiver. An aperture and an absorber make up the receiver. The aperture accepts the dish's solar radiations, and the absorber delivers the thermal energy to the Stirling engine's working gas. Stirling engine then turns the heat energy into mechanical energy, which is finally converted into electricity [42].

Figure 2.8. Eurodish collector [43].

Some information about solar Stirling systems that have been tested. Stirling engine used in Advanco’s Vanguard System was a United Stirling 4-95 Mark II kinematic Stirling engine. This engine provided 25kW. During the 18-month test phase, the engine operated for 2000 hours and recorded a 29.4% solar-to-electric conversion efficiency. SOLO Kleinmotoren manufactured a V-161 kinematic Stirling engine with a power rate of 10 kW shown in Figure 2.8. The system started operating in 1997 and operated for more than 25000 hours. The solo Stirling engine is an alpha arranged with separate, single-acting compression and expansion pistons. Cummins power generation built a 25 kW system using the Aisen-Seiki engine which is a double-acting 4-cylinder engine. This engine used helium as a working fluid [44].

Ripasso Dish Stirling with a DNI value of 960 W/m^2 provided 31.5 kW. Ripasso dish-Stirling breaks the existing world record in energy conversion efficiency from solar to electricity (32%), making it a cutting-edge system in concentrated systems [45].

2.3. SOLAR DISH STIRLING -BASED HYDROGEN PRODUCTION

2.3.1. SOLAR DISH STIRLING

The Solar Dish Stirling, together with the central receiver and parabolic trough, is one of the devices for concentrated solar power. This device focuses sunlight by a factor of up to 3000. Once the sunlight has been concentrated, it is directed to the place of the receiver. The receiver absorbs thermal energy and transmits it to the system's working fluid. Thermal energy from the working fluids is delivered to the Stirling engine as energy input. Using repeated heating/cooling of working fluids in a closed loop, the engine transforms externally supplied thermal energy into mechanical torque, which powers the generator to create electricity [46]. With the obtained electricity electrolyzer could be supplied for hydrogen production. The Proton Exchange Membrane (PEM) electrolyzer is regarded as one of the most promising hydrogen-generation technologies based on renewable energy resources.

In the study, a simulation for a home application was created. Home appliance consumption estimates were computed and predicted based on demands. There is a solar dish, a compressor, hydrogen tanks for storage, and a fuel cell in the modeled system. A Solar Stirling engine is used in this module to generate electricity from the sun. This electric energy is directly used to meet home demands, with any excess, electricity supplied to an electrolyzer for generating hydrogen by water electrolysis. The hydrogen is kept as a compressed gas in specific tanks and used as an energy source. When the power demand exceeds the direct supply, fuel cells are operated to generate energy from the stored hydrogen [47].

A case study conducted by Ouai, Moussaoui, and Merzhab in Eastern Morocco using equal capacities to compare PV hydrogen production with Solar Dish Stirling hydrogen production. It was discovered that Solar Dish Stirling's electricity output is 15.89 MWh and PV-based electricity production is 14.07 MWh per year, creating 302.2 kilograms of hydrogen for Solar Dish Stirling and 267.8 kg of hydrogen for the PV system. The result indicates that the hybrid system constructed that the Dish Stirling systems create more hydrogen[48].

A hybrid system constructed by Dulal and Sinha in 2014, consists of a Solar Dish Stirling, diesel generator, fuel cell, water electrolyzer, and battery storage device. The power delivered to the load is the sum of the output powers from the diesel generator, the dish-Stirling solar thermal system, the fuel cell, and the battery energy storage system. The aqua electrolyzer absorbs changes in solar thermal energy by generating hydrogen gas, which is then fed into a fuel cell generator[46].

A system is proposed that includes Dish-Stirling devices to convert solar radiation into electricity for the operation of RSOC. Additionally, waste heat is collected for seawater distillation using DCMD technology. Such a system would result in a solar-only, self-sufficient, and flexible multi-generation facility that can be arranged for different output combinations of hydrogen, electricity, and fresh water. The proposed plant is designed to supply 500 kW 24 hours a day according to the Nordic climate. The results show that, with an RSOC of 70 stacks with 200 cells, 175 units of 25 kW dish-Stirling, and a 7250 m PTSC, the plant was able to not only fulfill the steady demand but even increase the stored hydrogen for all days evaluated[49].

Stirling engine is capable to provide enough energy to an electrolytic cell. It operates in an energy-efficient way following the basis of thermal expansion and contraction in a closed-loop system. Stirling engines can be sourced from solar energy with a dish concentrator. In practice, the engine has exhibited greater than 40% efficiency for a variety of heat energy sources. Stirling energy systems holds the record for heat input to electrical power output for one of their solar dish Stirling engines, with 31.25% of solar energy converted to grid-level electricity. When compared to solar PV with the same energy capacity, the Stirling engine can be built using less expensive materials. Furthermore, the conversion efficiency of most typical solar PV designs is less than 20%, making it less appealing for hydrogen production. Thus, based on conversion efficiency and cost-effective design materials, the Solar Stirling engine system is believed to be a preferable alternative for generating energy for hydrogen gas generation [50].

2.3.2. WATER ELECTROLYZER

The electricity produced by renewable energy sources can be transformed into chemical energy using electrolyzer, which can then be transformed back into electricity using fuel cells. Water electrolysis is the process of splitting water into hydrogen and oxygen. A practical technique for carbon-free hydrogen production from renewable sources using electricity.

H_2 is typically produced with more than 99.8% purity from water electrolyzers and is compatible with renewable energies. This type of electrolyzer's primary drawback is its high energy requirement. Although a water-based electrolyzer should operate at a voltage of 0.23 V in theory, in practice it needs 1.4 V or more to oxidize into O_2 and H_2 ions [51].

There are different types of electrolyzers these are, polymer electrolyte membrane electrolyzers, alkaline electrolyzers, and solid oxide electrolyzers. In Table 2.2 specifications of these systems are shown. These electrolyzers operate in different temperatures and sizes. An alkaline electrolyzer uses a solution of mainly KOH to optimize ionic conductivity. When a direct current is delivered to the electrodes, the cathode produces hydrogen, and the anode produces oxygen. The disadvantage of alkaline is that it is corrosive. There is no need for a liquid electrolyte for PEM electrolyzers. A gas-tight thin polymer membrane is used as the electrolyte in this case. Nafion is the most often utilized membrane. PEM electrolyzers have a shorter lifetime than alkaline electrolyzers since this is the essential component. Solid oxide electrolyzers are an advanced idea of high-temperature (up to 1000 ^oC) water or steam electrolysis, resulting in higher efficiency than alkaline or PEM electrolyzers [52].

Table 2.2. Electrolyzer types [53]

Specification	**Alkaline**	**PEM**	**SOE**
Cell temperature, (^oC)	60-80	50-80	900-1000
Cell pressure, bar	<30	<30	<30
Current density, (A/cm^2)	0.2-0.4	0.6-2.0	0.3-1.0
Cell voltage, (V)	1.8-2.4	1.8-2.2	0.95-1.3
Power density, (W/cm^2)	Up to 1.0	Up to 4.4	-
Voltage efficiency, (%)	62-82	67-82	81-86
Energy consumption, (kWh/Nm^3)	4.5-7.0	4.5-7.5	2.5-3.5
H_2 production, (Nm^3/hr)	<760	<30	-
Stack lifetime, (h)	<90000	<20000	<40000
System lifetime, year	20-30	10-20	-
H_2 purity, %	>99.8	99.999	-
Cold start-up time, min	15	<15	<60

PEM water electrolysis is aligning with PEM fuel cell technology in that electrolytes are solid polysulfonated membranes. This technology has numerous advantages, including lower gas permeability, high proton conductivity and current density, compact design, high-pressure operation, quick response, and operation at lower temperatures. PEM water electrolysis is a promising approach for converting renewable energy to pure hydrogen and producing oxygen as a byproduct.

Water is fed into the device, which electrochemically separates it into hydrogen at the cathode and oxygen at the anode side. Water is separated into oxygen, protons, and electrons when it is pumped to the anode side. Protons flow through the proton-conducting membrane to the cathode. The electrons depart the anode via the external circuit, activating the process. Protons and electrons unite to generate hydrogen on the cathode side [54].

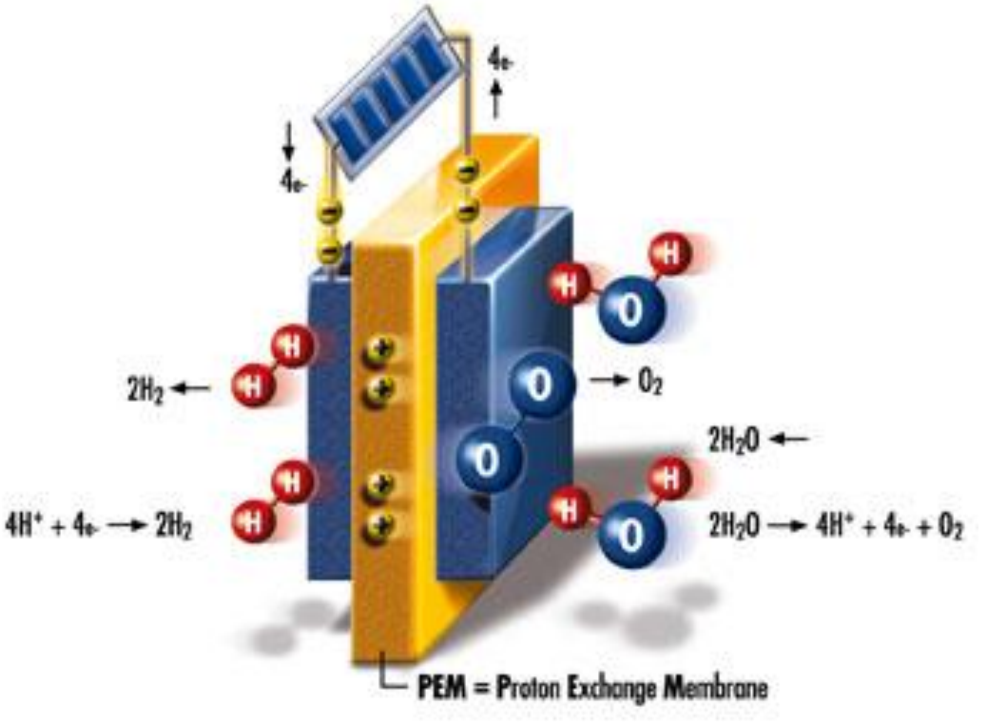


Figure 2.9. Working principle of PEM water electrolysis [55].

In Figure 2.9 the structure of the PEM Water Electrolyzer is represented. The reaction occurs in the anode; cathode side and overall equation as follows.

Anode: $H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^-$ (2.1)

Cathode: $2H^+ + 2e^- \rightarrow H_2$ (2.2)

Overall: $H_2O \rightarrow H_2 + \frac{1}{2}O_2$ (2.3)

2.3.3. HYDROGEN COMPRESSION

Once compressed, hydrogen can be kept in tanks for later use. Hydrogen can be compressed using a variety of tools and techniques. The three primary categories of these compressors are positive displacement, dynamic, and thermal. Types of compressors can be seen in Figure 2.10.

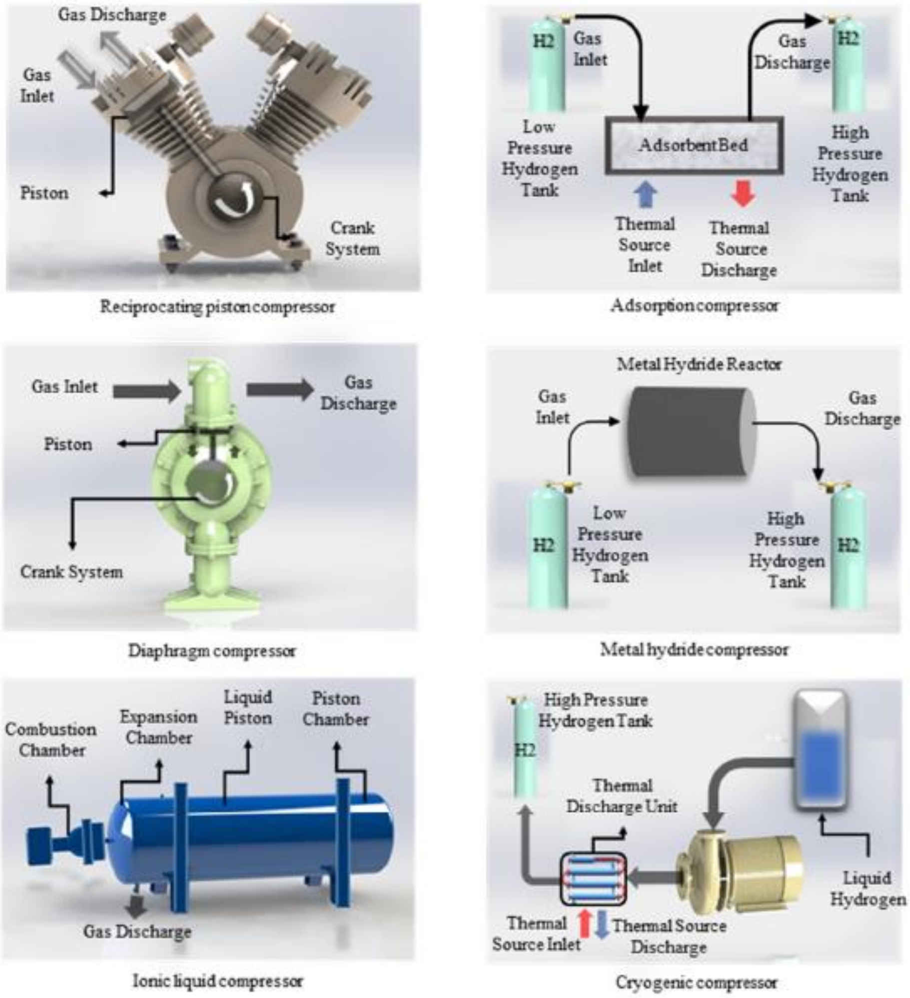


Figure 2.10. Hydrogen compressors [56].

One of the positive displacement types of compressors is the reciprocating compressor, which uses pistons that move back and forth to alter the volume. As one of the positive displacement types, the diaphragm used in a compressor changes where the gas is located. In dynamic types, the gas is accelerated by spinning parts. The following are drawbacks of mechanical compressors. First, they use a lot of electricity. Additionally, they have drawbacks such as unstable sections deforming over time and moving parts requiring continuous lubrication [56].

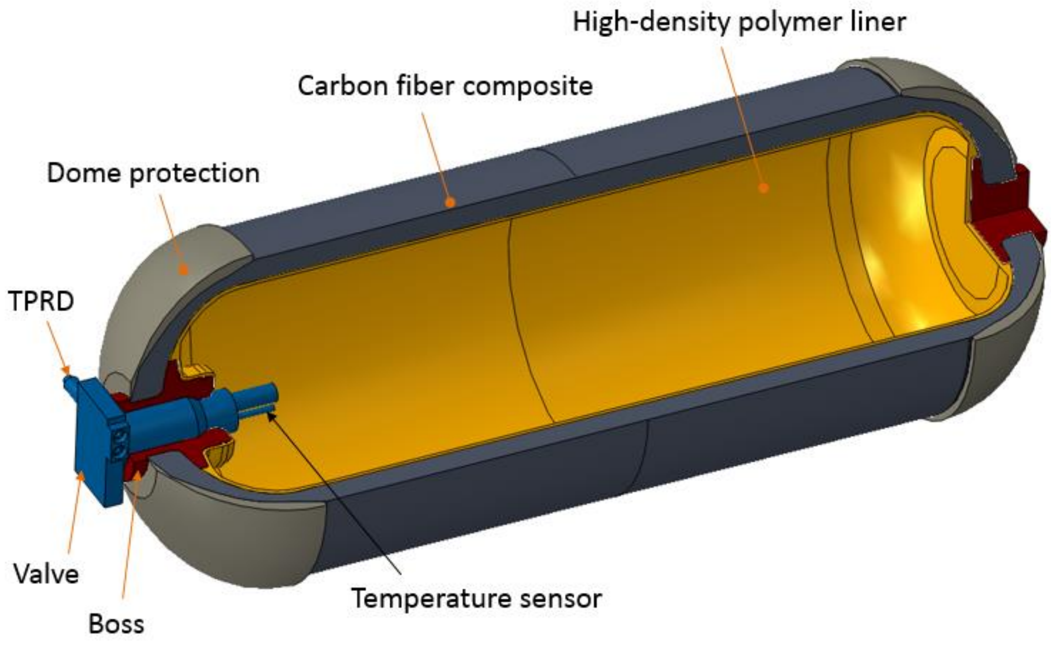
2.3.4. HYDROGEN STORAGE

Excess energy can be converted to hydrogen for storage. Then it could be used directly burned when energy is needed. Hydrogen storage systems must have high volumetric and gravimetric energy densities, quick energy intake and release kinetics, and be operable at standard operational temperature and pressure. It must be safe by design, and economically feasible. Different hydrogen storage systems are required depending on the component for the demand [57].

Hydrogen can be stored in gaseous form. The behavior of hydrogen under high pressure has been extensively studied. In composite tanks, hydrogen has recently been compressed to 1000 bars. These storage tanks are made from composite materials. Tanks are made lighter by using carbon fiber-reinforced composites [58]. In Figure 2.11 a hydrogen tank is shown with its layers. Pressure tanks are classified into four kinds based on their design. Types of tanks are shown in Table 2.4 [59].

Table 2.3. Hydrogen tank types

Tank Type	Description
Type I	Metal tank with no wrapping
Type II	Metal tank, having reinforcement fiber wrapping only in the cylindrical center part
Type III	Aluminum tank, surface wrapped with reinforcement by fiber
Type IV	plastic tank, fiber wrapping the entire surface



TPRD = Thermally Activated Pressure Relief Device

Credit: Process Modeling Group, Nuclear Engineering Division. Argonne National Laboratory (ANL)

Figure 2.11. Hydrogen tank [60].

CHAPTER 3

3. ANALYSIS OF THE PROPOSED SYSTEM

3.1. ANALYSIS OF GREEN HYDROGEN PRODUCTION SYSTEM

The system has four major components, Ripasso Dish Stirling which has the cutting edge technology in these systems [61], PEM water electrolyzer, hydrogen compressor and tanks for the storage of the produced hydrogen.

Solar dish Stirling system follows the sun and provides electricity production in optimum condition. The sun's rays hit the concentrator and are collected at the focal point. This thermal energy is transferred to the Stirling engine with the help of the receiver located at the focal point. The heated Stirling engine starts to move and converts thermal energy into mechanical energy. The alternator, which is connected to the Stirling engine, begins to produce electricity with the movement of the Stirling engine. When the electricity produced is sufficient to run the electrolyzer and compressor, the electrolyzer kicks in and hydrogen production begins. The produced hydrogen is compressed with the help of a compressor and stored in tanks. When the tank is full, the stored hydrogen is sold. The electrolyzer can work for a maximum of 10 hours a day. After the electrolyzer and compressor work, the excess electricity produced is sold to the grid. When enough power is not produced to run the electrolyzer and the compressor, the offset strategy is followed, the total electric power produced during the day is taken as a basis and the electrolyzer is operated according to this total power.

Microsoft EXCEL was used for the analysis of the proposed system. The collected solar data, as well as the specifications of the fuel cell and compressor, are written down for computation.

3.2.SOLAR DATA COLLECTION

Solar radiation measurements were taken according to the Atilim University Incek Campus, Ankara, (39.813 N, 32.726 E). The location of the taken data is shown in Figure 3.1. A Meteorology station represented in Figure 3.2 was installed to obtain solar radiation, temperature, wind speed, humidity, and atmospheric pressure.

Figure 3.1 Location of the meteorology station [61].

Figure 3.2 Meteorology station [62].

Meteorology station is manufactured by Davis Instruments. Device can measuere temperature with 0.1°C resolution, humidity with 1% resolution and solar radiation with 1 W/m^2 resolution [63].

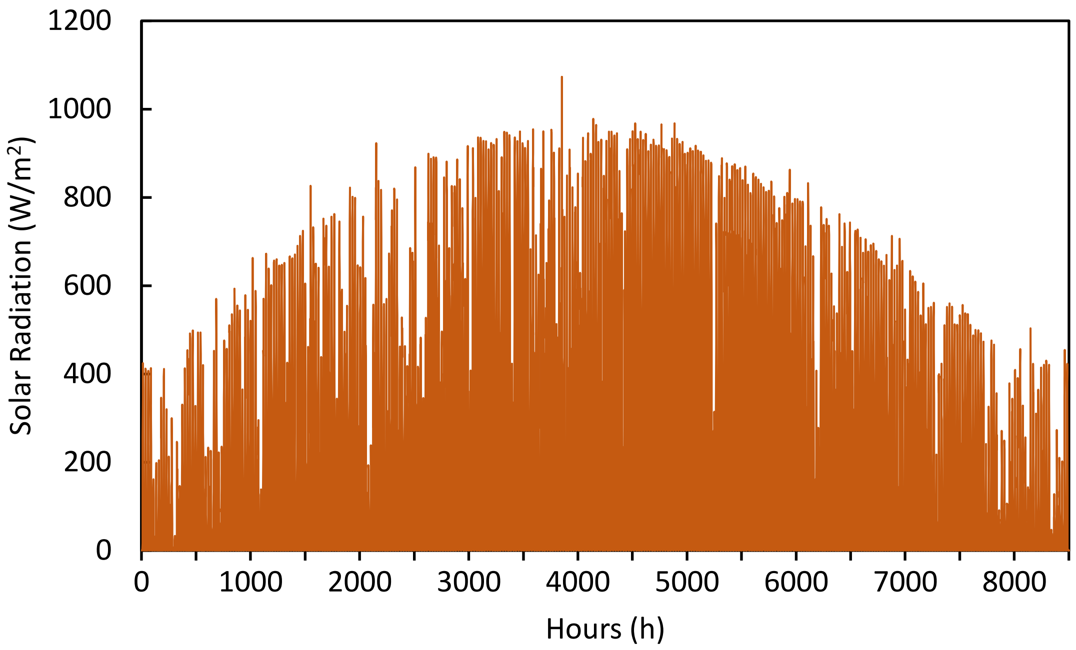


Figure 3.3 Hourly solar radiation

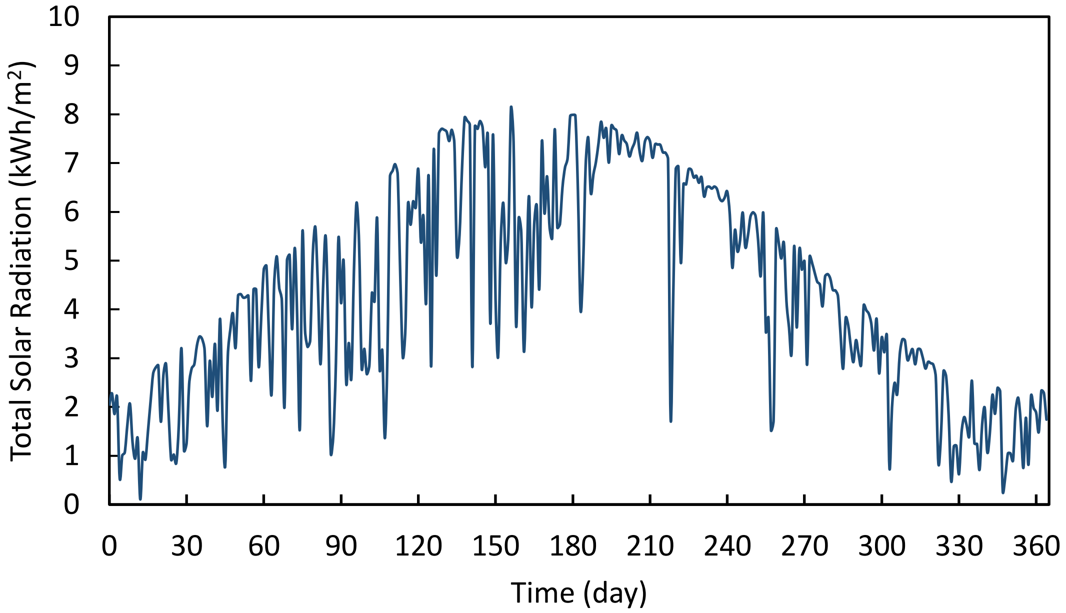


Figure 3.4 Daily total solar radiation

Figure 3.3 and 3.4 depicts the solar radiation values attained on our campus starting from 01/01/2021 to 01/01/2022. Hourly measurements were taken and represented in Figure 3.3. Total daily measured radiation levels are presented in Figure 3.4.

3.3.COMPONENTS OF PROPOSED SYSTEM

The Ripasso CSP's net electric production is directly proportional to solar flux. 31.5 kW net electric power is obtained at a DNI value of 960W/m^2. This system has an efficiency rate of 32% making it the best in the world. The dish is installed at the University of Palermo. The specifications of the Ripasso dish are listed in Table 3.1.

Table 3.1 Ripasso dish-stirling specs [64].

Dish Diameter	12	m
Focal Length	7.45	m
Effective aperture area	101	m^2
Geometric concentration ratio	3217	-
The reflectivity of clean mirrors	95	%
Total Height	14	m
Total weight	8700	kg
Occupation of area	500	m^2
Type of Stirling Engine	4 cylinders double acting	-
Displaced Volume	4x95	cm^3
Typical output	31.5 @2300 rpm	kW
Receiver Temperature	720	^{0}C
Working Gas	Hydrogen	-
Max Gas pressure	200	bar
Weight of engine	700	kg
Total efficiency	32	%

Thanks to the tracking system, thermal energy is uniformly distributed on the receiver surface. Thermal energy absorbed by the receiver heats the working fluid hydrogen to 720 ^{o}C in the stirling engine. This heat is converted to mechanical energy and by an alternator is converted to electricity.

Figure 3.5. Ripasso dish-stirling [65].

PEM water electrolyzer was chosen for green hydrogen production. It will work with the electricity obtained from the solar dish stirling. The maximum operation time per day is 10 hours. The selected PEM water electrolyzer has the following characteristics in Table 3.2 [53]. Regards to the characteristics total number of cells in the electrolyzer are 15. With a total stack voltage of 22.4 V.

Table 3.2. PEM water electrolyzer [53].

Definition	Value	Units
Cell Area	200	cm^2
Current Density	1	A/ cm^2

Net Power	4000	W
Parastic Losses	12%	
Cell Voltage	1.5	V

In the constructed system, the hydrogen compressor is crucial. It is possible to store more hydrogen by compressing it with a compressor. The Hydrapoc Company's C03-03-70/140LX compressor was selected for your system. The compressor has a power rating of 2.3 kW and can compress hydrogen to 200 bar pressure. It is a multistage compressor. The second stage cylinder diameter is smaller than the first stage. With this arrangement interstage cooling occurs between cylinders and increases the compression ratio[66]. In Figure 3.6 a multistage hydrogen compressor is shown.

Figure 3.6. Hydrogen compressor [66].

Produced hydrogen from the electrolyzer is stored in the tanks. Type 2 tanks are used. Type 2 metal tank has reinforcement fiber wrapping only in the cylindrical center part. It will have a volume of 300 L with a pressure level of 200 bar.

3.4. OPTIMAL STRATEGY OF THE PROPOSED SYSTEM

Figure 3.7 shows the proposed system design. solar dish stirling is linked to the power grid. Because the electrolyzer operates on direct current, the mains connection includes a rectifier second major component, the electrolyzer is connected to the grid by a rectifier because its operation current is DC. The electrolyzer is fed with pure water. In the water supply pipe, there is a check valve and pump units. Pressure and mass flow rate sensors are used to offer controlled operation on the line. At the electrolyzer output, there is a hydrogen line and an oxygen line. Oxygen is released into the air in a controlled and safe manner. The extraction of oxygen from the anode side together with water creates difficulties in terms of oxygen storage [67]. Furthermore, using this technique for oxygen production and storage necessitates the purchase of extra equipment such as a compressor storage tank which leads to additional costs [68]. The hydrogen produced flows via the check valve and is delivered to the compressor, where it is compressed to 200 bar pressure and stored in the hydrogen tank. When the tank is full it is switched to the empty one. This line has pressure, temperature, and mass flow rate sensors that are used to control the system.

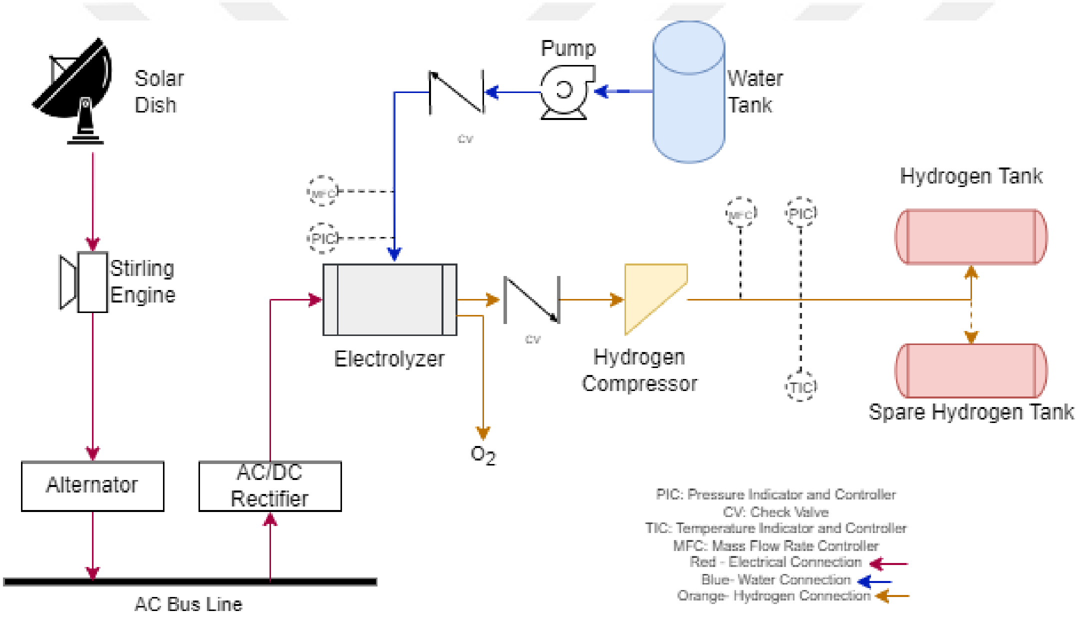


Figure 3.7. Proposed system design.

Figure 3.8. illustrates the system's working and offsetting technique. Solar Dish Stirling receives sunlight. The Solar Dish Stirling starts to generate electricity. If the amount of electricity produced exceeds 6.78 kW, the electrolyzer working hours are calculated. Excess electricity is provided to the system if the working hours exceed 10 hours. If it is less than 10 hours, the electrolyzer is activated, and the remaining amount is sent into the system. If there is production but not enough to power the electrolyzer, the excess electricity is fed into the system.

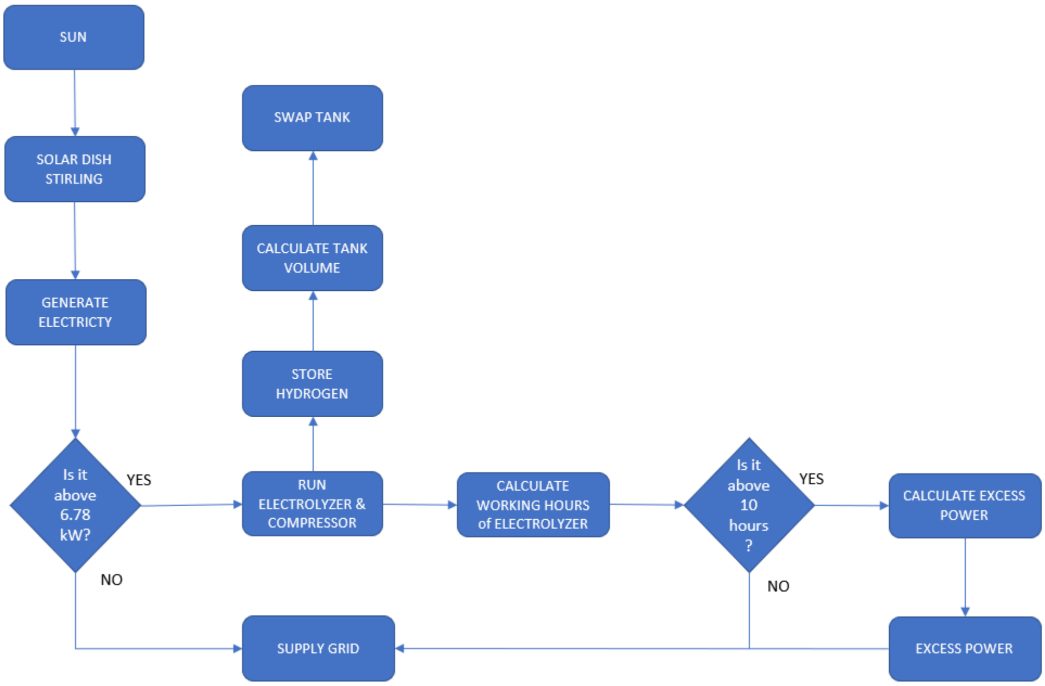


Figure 3.8. Proposed system flow chart.

3.5. ANALYSIS OF THE PROPOSED SYSTEM

3.5.1. SOLAR CALCULATION

The average solar radiation is determined by the duration of the radiation. Throughout the year, an average of 322 W/m^2 is reported, based on the duration of sunshine. On 10/06/21, the highest value was measured as 1073 W/m^2. In line with these measurements, it was decided to operate a 4 kW electrolyzer.

In Figure 3.9, the energy balance equations of the solar dish stirling system are shown. Energy calculations can be made with incoming radiation, material properties, heat transmission coefficients and temperature values [69].

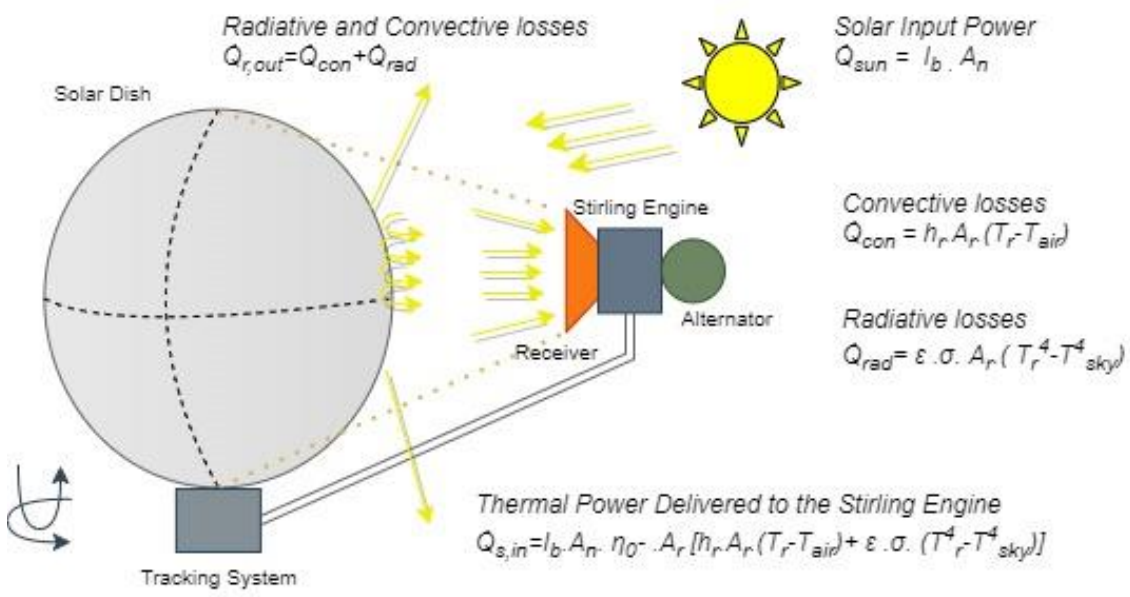


Figure 3.9. Solar dish energy balance [69]

Equation 3.1 may be used to compute the rate of solar energy reflected off the mirrors of a collector that is continually following the sun.

$$\dot{Q}_{sun} = I_b \cdot A_n \tag{3.1}$$

The solar beam radiation is denoted by Ib. A represents the overall collector aperture area. Equation 3.2 can be used to calculate the net effective surface of the dish collector.

$$A_n = \eta_m \cdot A_a \tag{3.2}$$

η_m denotes the effective reflective area losses. The cavity receiver's effective absorption of concentrated solar power can be found in Equation 3.3.

$$\dot{Q}_{r,in} = \eta_0 \cdot \dot{Q}_{sun} \tag{3.3}$$

η_0 represents the concentrator system's optical efficiency. Equation 3.4 may be used to calculate the optical efficiency of the concentrator system.

$$\eta_0 = \rho \cdot \gamma \cdot \alpha \cdot \eta_{cycle} \tag{3.4}$$

Where ρ is the clean mirror reflectance, η_{cycle} is a factor which considers that takes mirror cleanliness, γ is the collector's intercept factor, and α is the effective cavity receiver absorptance.

Total power loss from the receiver is defined in Equation 3.5. The effects of relative humidty, wind speed and other minor environmental effets are neglected.

$$\dot{Q}_{r,out} = \dot{Q}_{con} + \dot{Q}_{rad} \tag{3.5}$$

Convective loss is calculated by Equation 3.6.

$$\dot{Q}_{con} = h_r \cdot A_r \cdot (T_r - T_{air}) \tag{3.6}$$

Where h$_r$ is the cavity receiver's effective convective coefficient and A$_r$ is the surface area of the receiver's aperture. Equation 3.7 is used to calculate radiation losses.

$$\dot{Q}_{rad} = \varepsilon \cdot \sigma \cdot A_r(T_r^4 - T_{sky}^4) \tag{3.7}$$

Where, ε is the cavity receiver's effective emissivity, σ is the Stefan–Boltzmann constant.

Sky temperature can be calculated by Equation 3.8.

$$T_{sky} = 0.552 \cdot T_{air}^{1.5} \tag{3.8}$$

Equations 3.9, 3.10, and 3.11 can be used to express the thermal power delivered to the Stirling engine.

$$\dot{Q}_{s,in} = \dot{Q}_{r,in} - \dot{Q}_{r,out} \tag{3.9}$$

$$\dot{Q}_{s,in} = I_b \cdot A_n \cdot \eta_0 - A_r \cdot [h_r \cdot (T_r - T_{air}) + \varepsilon \cdot \sigma \cdot A_r(T_r^4 - T_{sky}^4)] \tag{3.10}$$

$$\eta_c = \frac{\dot{Q}_{s,in}}{Q_{sun}} = \eta_0 - \frac{1}{I_b C_g} \cdot [h_r \cdot (T_r - T_{air}) + \varepsilon \cdot \sigma \cdot A_r(T_r^4 - T_{sky}^4)] \tag{3.11}$$

The geometric concentration ratio is calculated by Equation 3.12.

$$C_g = \frac{A_n}{A_r} \tag{3.12}$$

The mechanical output power is determined by the efficiency and input thermal power of the Stirling engine (Equation 3.13).

$$\dot{W}_s = \eta_{S,ex} \cdot \dot{Q}_{s,in} \tag{3.13}$$

The efficiency of the Stirling engine, in turn, might be broadly related to the engine's reversible Carnot efficiency. A fully functional regenerator permits heat rejected during isochoric rarefaction to be transferred during isochoric compression. This Stirling cycle has the same Carnot thermal efficiency as the prior one.

$$\eta_S = \eta_{S,ex} \cdot \eta_{s,c} \tag{3.14}$$

$\eta_{S,ex.}$ is the exergetic efficiency of the engine. The Carnot cycle efficiency, which depends on both the heat input and heat rejection temperatures T_h & T_c. The ratio of the theoretical mechanic power output of the ideal Stirling cycle running at limit temperatures Th & Tc is shown in Equation 3.15.

$$\eta_{S,C} = (1 - \frac{T_c}{T_h}) \tag{3.15}$$

$\eta_{S,ex}$ presents the ratio between the actual mechanical power output $\dot{W}$ and the maximum mechanical power. $\eta_{S,ex}$ is found between 0.55-0.88. Often assumed as 0.5. The reason is the performance depends on many factors.

Equation 3.16 shows the thermal power that must be dissipated by the cooling system.

$$\dot{Q}_{s,out} = \dot{Q}_{s,in} - \dot{W}_s = 1 - \eta_{S,ex} \cdot \dot{Q}_{s,in} \tag{3.16}$$

The curve between the engine's thermal input power and mechanical output power can be approximated using linear regression as Equation 3.17.

$$\dot{W}_s = (a_1 \cdot \dot{Q}_{s,in} - a_2) R_T \tag{3.17}$$

Reference temperature can be found in Equation 3.18.

$$R_T = T_0 / T_{air} \tag{3.18}$$

Knowing the mechanical output, it is possible to calculate the electric power by Equation 3.19.

$$\dot{E}_g = \eta_e \cdot \dot{W}_s \tag{3.19}$$

The net electrical output of the Dish can be calculated by subtracting auxiliaries such as the cooling system, tracking, and pumps. This can be found in Equations 3.20 and 3.21.

$$\dot{E}_n = \dot{E}_g - \dot{E}_p \tag{3.20}$$

$$\dot{E}_p = \dot{E}_{p,t} - \dot{E}_p, d \tag{3.21}$$

The net electrical output is expressed by Equation 3.22.

$$\dot{E}_n = \eta_e \cdot \eta_0 \cdot a_1 \cdot A_a \cdot R_T \cdot I_b - [\eta_e \cdot a_1 \cdot \dot{Q}_{s,out} + a_2 \cdot R_T + \dot{E}_p] \tag{3.22}$$

The net output of the solar dish system is also as equation 3.23 [47].

$$P_{SE} = \varepsilon . A_{mirr} . \eta_{conc} . \eta_{rec} . \eta_S . \eta_{EG} \tag{3.23}$$

The mirror area can be found in Equation 3.24 [47].

$$A_{mirr} = \frac{\pi D^2}{4} \tag{3.24}$$

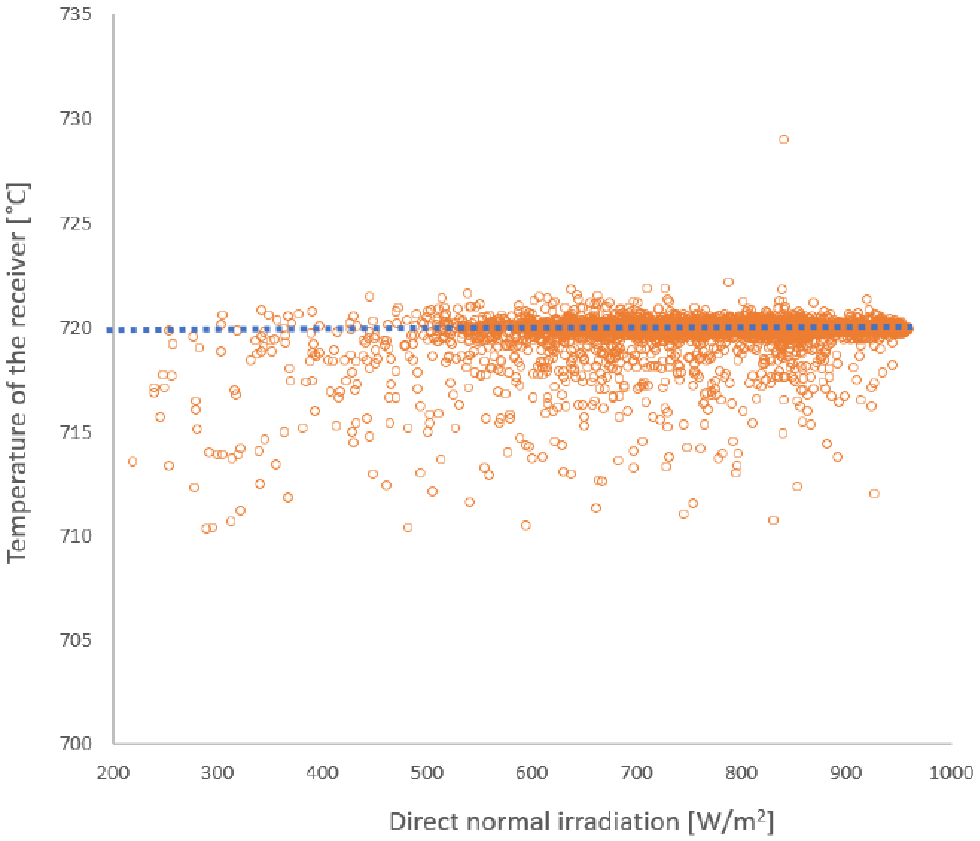


Figure 3.10 Solar dish receiver temperature [69].

In Palermo, the solar radiation values measured during the test were assessed as a function, and the temperature change values in the receiver were calculated. Figure 3.10 shows the average value of the receiver is 720^0C. Between $500 W/m^2$ and $1000\ W/m^2$, the temperature of the receiver is 720 ^{o}C degrees [69].

3.5.2. ELECTROLYZER CALCULATON

The design power for the electrolyzer is defined by Equation 3.25.

$$P = Current\ Density \times Cell\ Area \times V_{stack} \qquad (3.25)$$

Cell area and current density are the characteristics of the electrolyzer. Once knowing the actual required power for the electrolyzer must set the design power with efficiency value. After knowing the design power, stack voltage can be driven by equation 3.25.

To find the number of cells for the electrolyzer, cell voltage must be known, which is a characteristic value depending on the electrolyzer. The n_{cell} can be calculated from Equation 3.26.

$$n_{cell} = V_{stack}/V_{cell} \tag{3.26}$$

Faraday's laws in the electrolysis are used to determine the cell number of the PEM Electrolyzer. Since the characteristics of the electrolyzer are known. Production of hydrogen can be calculated from Equation 3.27.

$$n_{H_2} = \frac{n_{cell} \times i}{2 \times F} \tag{3.27}$$

where; n_{cell} is the number of cells in the electrolyzer. F is the Faradays constant and i is the current density of the electrolyzer. n_{H2} represents the value of produced hydrogen in mol per second mol/s.

Applying the principle to find oxygen production by the electrolyzer is shown in Equation 3.28.

$$n_{O_2} = \frac{n_{cell} \times i}{4 \times F} \tag{3.28}$$

3.5.3. HYDROGEN STORAGE CALCULATION

Hydrogen can be stored in compressed tanks. As with any gas, there are temperature, volume, and pressure characteristics. According to Avogadro's Law, the volume of gas can change proportionally to the mole number under constant pressure and temperature. According to this approach tank volume can be calculated by Equation 3.29.

$$P \cdot V = n \cdot R \cdot T \tag{3.29}$$

The constants in ideal gas law are; P is pressure, V is volume, n is the number of moles, and R is the ideal gas constant (8.314 kJ/kmol.K). Ideal gas low can give an estimation of what volume tank is required however this approach isn't appropriate to use for exact calculation because of the behavior of gases. Because molecules interact with one another, real gases diverge from the ideal gas law. Propellant forces between molecules assist in the expansion, whereas attracting forces assist in compression.

A more reliable approach to calculate the volume of the storage tanks is using the Van Der Waals real gas equation. Van Der Waals equation is shown in Equation 3.30.

$$\mathrm{P} \cdot \mathrm{V} = \frac{\mathrm{n \cdot R \cdot T}}{\mathrm{V - n \cdot b}} - \frac{\mathrm{n^{2a}}}{\mathrm{V^2}} \tag{3.30}$$

Where a is the net intermolecular attraction and b is the finite volume of molecules.

$$a = \frac{27}{64} \times \frac{R^2 T_c^2}{P_c} \tag{3.31}$$

$$b = \frac{R}{8} \times \frac{T_c}{P_c} \tag{3.32}$$

Isentropic compression is performed by an ideal compressor by ignoring internal friction, leakage, and assuming that it is adequately insulated. The amount of power need by the compressor can be calculated from the following Equation 3.33.

$$P_{Comp} = 2.31 \frac{k}{k-1} \frac{T_2 - T_1}{M} Q_m \eta_{comp} \tag{3.33}$$

P_{comp} is the power of the compressor, T_1 &T_2 indicates the inlet and outlet temperatures of the compressor, M represents the molar weight of the gas, Q_m shows the flow rate and k is the isentropic coefficient of the gas. 2.31 is the conversion of mass flow rate. simplified formula is based on t/h while the general formula is considering kg/s[70].

3.5.4. ECONOMIC ANALYSIS AND LEVELIZED COST OF ENERGY (LCOE) CALCULATIONS

The Levelized Cost of Electricity approach is a popular technique for determining the cost-effectiveness of power production technologies and whether developing technologies are achieving grid parity. The International Atomic Energy Agency IAEA developed the first LCOE approach in 1984, to compare costs between generating units. The LCOE is an excellent tool for determining whether a technology is promising or not. If the LCOE is equivalent to or lower than the traditional generation or retail pricing, it implies that developing technologies are competitive and can reach grid parity. Different parameters like capital cost, interest rate, and inflation rate have a significant impact on LCOE [71].

To calculate the difference between the historical and annual cost of capital, the real interest rate is used. Equation 3.33 shows the nominal interest rate to the yearly real interest rate.

$$i = \frac{i_0 - f}{1 + f} \tag{3.34}$$

Where i annual interest rate and i_0 is the nominal interest rate. f is the annual inflation rate. The same inflation rate is accepted for all costs. The capital recovery factor is used to compute the present value of a subvention based on the yearly real interest rate and time duration.

$$CRF = \frac{i_0(1+i)^N}{(1+i)^N - 1} \tag{3.35}$$

The LCOE provides an economic assessment. The LCOE is computed as the life cycle cost of the system divided by the energy output during the life of the system and is affected by project size and capacity, capital cost, lifespan, maintenance, and operating costs**.**

$$LCOE = \frac{Life\ cycle\ cost\ \$}{Life\ time\ energy\ production} \tag{3.36}$$

The economic parameters for LCOE calculation are given in Table 3.3. PEM electrolyzer, tank values are obtained from the literature [53]. Hydrogen compressor values are assumed.

Table 3.3. LCOE values for the components of the proposed system

Ripasso Dish Stirling [64]	
Investment Cost $I_{(t)}$	200525€ / 210551.3 $
Operation & Maintenance Cost $M_{(t)}$	3117€ / 3272.85$
Electricity Production $E_{(t)}$ kWh	47950.3 kWh
Lifetime Years	25
PEM Water Electrolyzer [53]	
Investment Cost $I_{(t)}$	4000$
Operation & Maintenance Cost $M_{(t)}$	604.2$
Lifetime Years	10
H_2 Production	376.99 kg H_2 = 11359.86 kWh
Compressor [72][53]	
Investment Cost $I_{(t)}$	3800$
Operation & Maintenance Cost $M_{(t)}$	300$
Lifetime Years	10
Storage Tanks [53]	
Investment Cost $I_{(t)}$	2905.8 $
Operation & Maintenance Cost $M_{(t)}$	14.529$
Lifetime Years	25

3.5.5. GREENHOUSE GAS EMISSIONS CALCULATION

The leading method of hydrogen production in the world is the natural gas reforming method. The most important reason for this is the maturation of the production technology and the possibility of hydrogen production to a large extent. However, in the natural gas reforming method, the CO_2 emission that is released alongside the hydrogen formed by the steam-methane reform causes my problem [73]. One of the key indicators for understanding this effect is how much CO_2 is created throughout the processes. The calculation method is based on hydrogen production and a constant facility-specific proportionality factor. This factor assumes that the carbon content of the natural gas or other fuel/feedstock remains constant over time and is based on previous data for the plant's consumption of fuel and feedstock as well as its generation of hydrogen. Equation 3.36 shows the calculation of CO_2 produced during the process.

$$E_{CO_2} = HP \times FR \times CCF \times COF \times \frac{44.01}{12.01} - R_{CO_2} \qquad (3.37)$$

Where $\mathrm{E}_{\mathrm{CO}_2}$ indicates the produced metric tons of CO_2 in a year, FR is the feedstock requirement per unit of output, CCF shows the carbon content factor of feedstock, COF which is a fraction represents the carbon oxidation factor of feedstock and the last $\mathrm{R}_{\mathrm{CO}_2}$ is the recovered CO_2 for other usages.

Another approach for the calculation of CO_2 emission is shown in Equation 3.37 where a hybrid model combines continuous emissions monitoring system. The fuel and feedstock mass balance method measures the amount of carbon present in all fuel and feedstock delivered to the facility as well as the carbon content of all products that leave the facility, under the presumption that all carbon present in the fuel and feedstock that enters the facility is converted to CO_2.

$$CO_2 = \sum_0^n((FSR \times CF) - S) \times 3.664 \times metric\ ton/1000 \qquad (3.38)$$

Where FSR is the daily supply rate of fuel and feedstock, CF is the carbon fraction in feedstock, S represents the carbon fraction diverted and accounted elsewhere, the 3.664 constant is the conversion factor of carbon to carbon dioxide and n shows the number of days in operation [74].

Table 3.4 Steam reforming hydrogen plant data

Definition	**Value**	**Unit**
Hydrogen production [75]	1.5	MNm^3/day
Natural gas feed [75]	392	Mg/day
The weight fraction of carbon in feedstock [76]	25	kg C/kg CH_4

Carbon content factor of feedstock [77]	0.995	-

With the values in Table 3.4, the emission values created by the steam reforming method were calculated.

CHAPTER 4

4. RESULTS AND DISCUSSIONS

4.1. ANALYSIS RESULTS

By observing Figure 4.1 it is seen that the electricity production of solar dish stirling increases in summer and the beginning of autumn months. Solar dish stirling can produce 47950.3 kWh/year, in Ankara Region. The highest production was found to be 33.87 kW with a radiation level of 1073 W/m^2. As seen in Figure 4.1, it is obvious that electric production is proportional to solar radiation. The minimum radiation value required for the solar dish stirling system to operate is 50 W/m^2. When this value is exceeded, the solar dish will begin to generate electricity. High working hours were found throughout the summer months, just as they were in production.

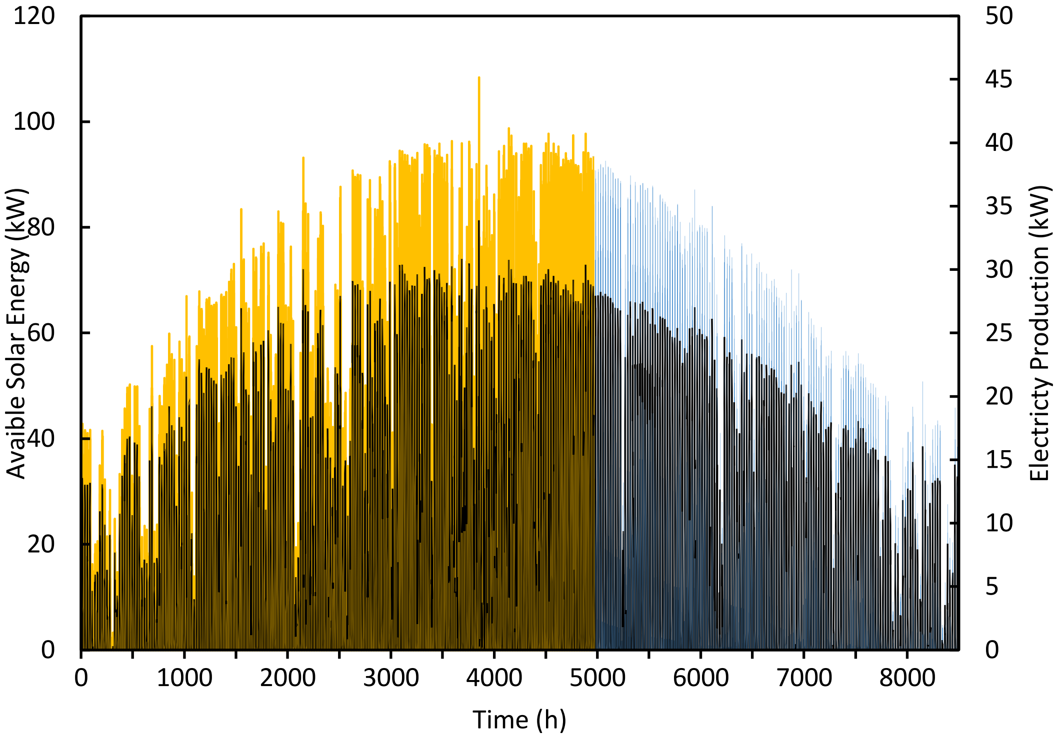


Figure 4.1. Solar dish hourly electricity production and available solar energy.

Measured sky tempereratue and air temperature are shown in Figure 4.2. Recorded highest temperature is 35.7 °C and average temperature is 11.79 °C all year.

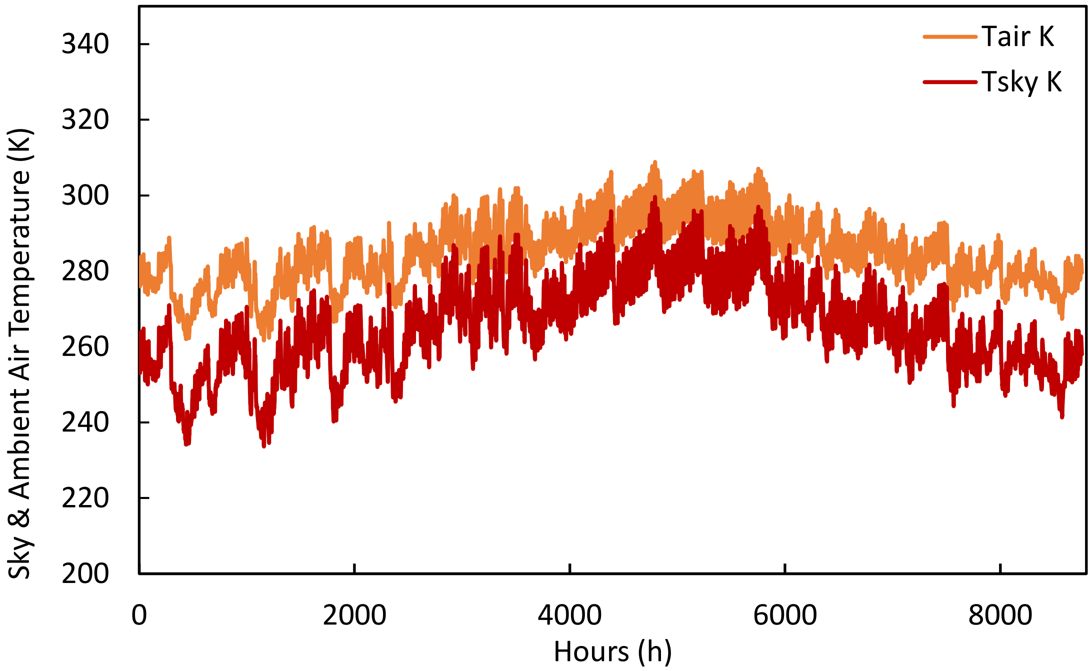


Figure 4.2 Sky & ambient temperature

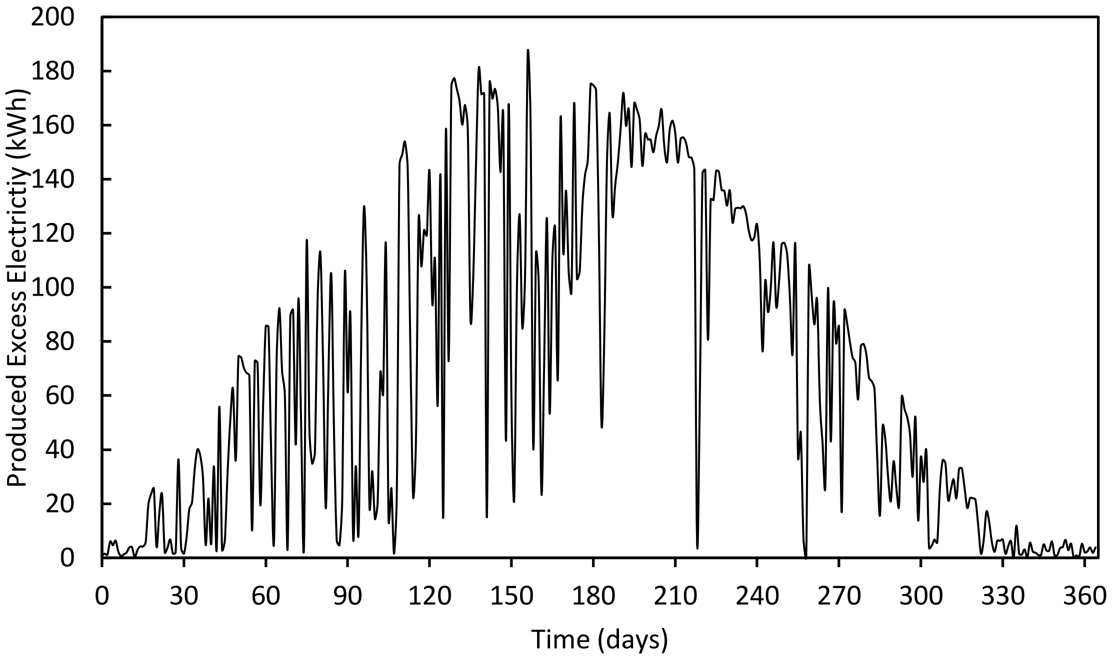


Figure 4.3. Total excess produced electricity

After supplying the electrolyzer total excess electricity produced from the Solar Dish Stirling is 25556 kWh. As is seen in Figure 4.3, the Solar Dish Stirling system produces more excess electricity in summer than in winter.

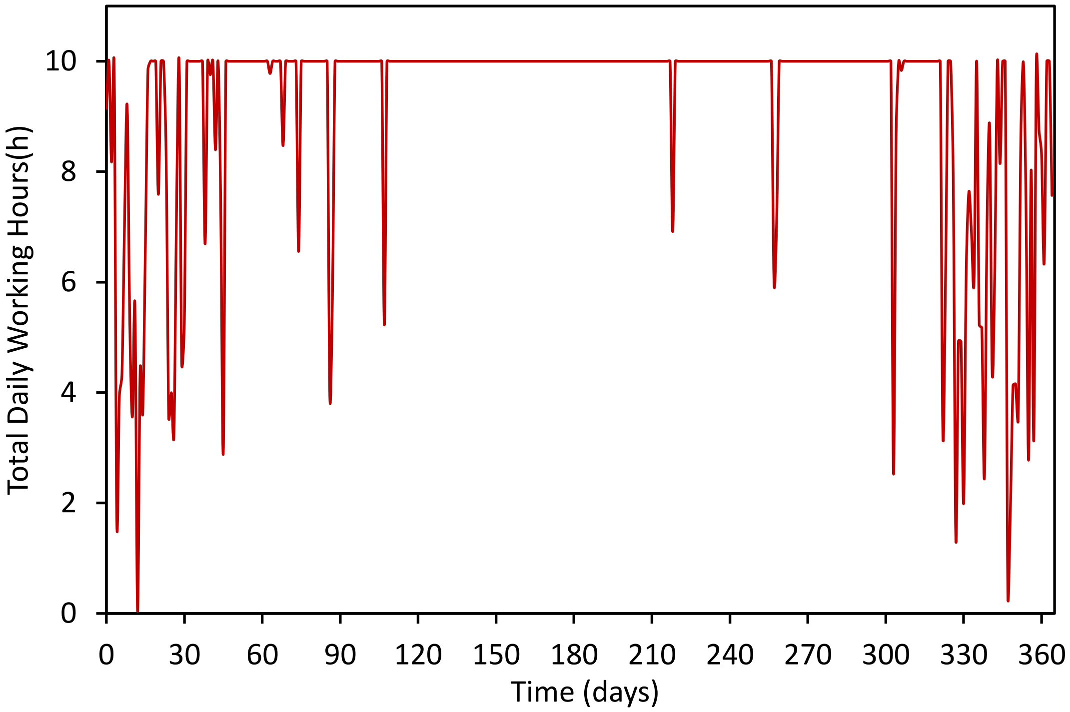


Figure 4.4. Electrolyzer daily working hours

In Figure 4.4. electrolyzer working hours are represented. Electrolyzer working hours have been increased to the optimum level by following the offset strategy. A total hydrogen production capacity was determined as 377 kg/year by working electrolyzer as 3341.5 hours per year.

Figure 4.5 illustrates the daily hydrogen production and total hydrogen production in a year. Looking at Figure 4.3. The selected hydrogen tank has a volume of 300 L and can hold a pressure of 200 bars which means it can store 4.843 kg of hydrogen. A total of 187015.19 moles of hydrogen was produced during the year. Total hydrogen production is 377 kg which can fill the tank 77 times in a year. If this hydrogen was produced by the steam reforming method, 7 kg of CO_2 would be released per kilo of hydrogen produced. The 377 kilograms of hydrogen that’s been generated, would have resulted in 2639 kilograms of CO_2 [78].

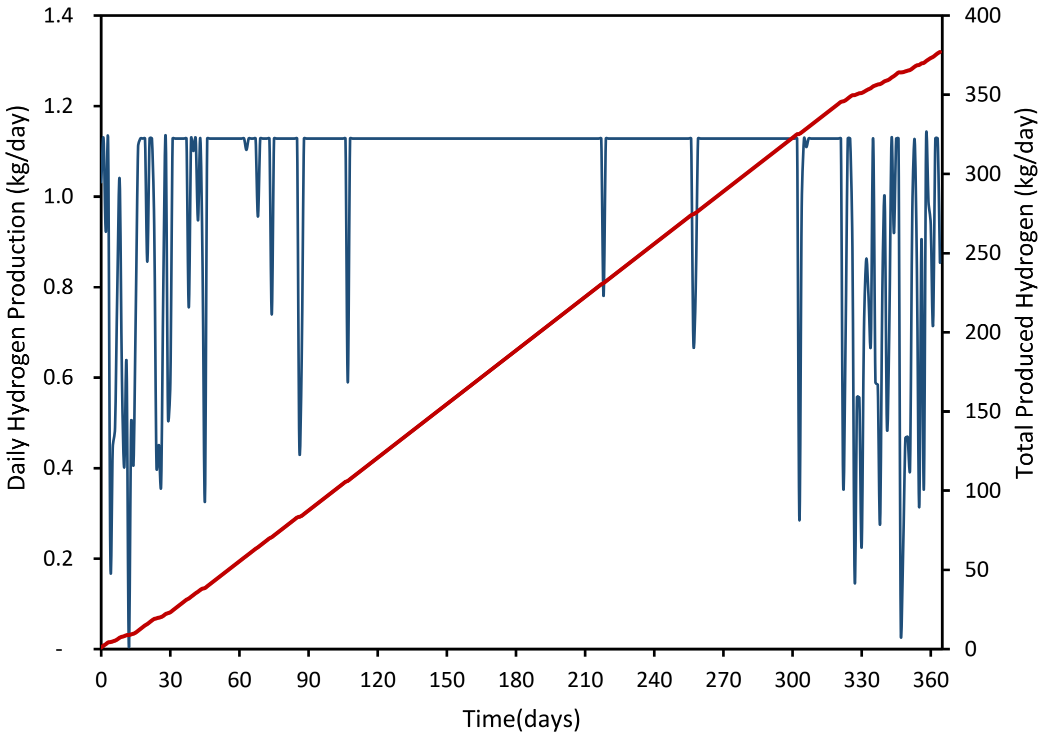


Figure 4.5. Daily hydrogen production and total hydrogen production in a year.

4.2.ECONOMIC ANALYSIS RESULTS

Levelized cost of energy measurement is crucial when investing. It is an excellent tool for determining the average total cost of constructing and operating the asset per unit of total electricity generated over an expected lifetime. The lifetime of the proposed system is proposed to be 25 years. The inflation rate in Turkey from November 2022 is 84.39% and the interest rate is 9% [79]. Capital Recovery Factor CRF is to be found 0.10 by the Equation (3.32).

The total investment cost of the system for 25 years is 229057.1 $. By using CRF value we convert the capital cost to a yearly base. The total operation and maintenance cost for the whole system is 4254.579 $. The total electricity production of Solar Dish Stirling is 47950.34 kWh and produced hydrogen is equal to 12564.97 kWh. With the obtained values the LCOE value of the system is 0.454$/kWh. Taking the statistics from IRENA, concentrated solar electricity LCOE value is 0.144 $/kWh however in these statistics Solar Dish Stirling systems are not involved. According to this average value, the cost of our system seems quite high, but according to the information from the IEA, it is at a level that can compete with the coal LCOE value. It should be chosen as a forward-looking strategy for a clean future.

4.3.GREENHOUSE GAS EMISSIONS RESULTS

The data of the plant producing hydrogen with steam reforming and the annual emission value were calculated for comparison. It s found out that the facility causes approximately 274 Mt of CO_2 emissions per year, plus production CO_2 for usage is not mentioned in the calculations. Obtained value approaches the 202 Mt value found in the literature review. Therefore, 7kg of CO_2 formation for 1kg of hydrogen production can be taken as a basis to compare emission levels for the green hydrogen system. In this direction, 377 kg of H_2 produced by the electrolyzer fed with Solar Dish Stirling would have created 2639 kg of CO_2 emissions if it had been produced by steam reforming.

CHAPTER 5

5. CONCLUSIONS

Green hydrogen production and renewable energy sources are critical to our future. Environmental and sustainable solutions will be an excellent substitute for fossil fuels. The importance of the worldwide study on this topic is expanding by the day.

In this thesis, green hydrogen production modeling was done with solar dish stirling from concentrated solar energy systems. This system is modeled on real data measured on our campus. Firstly, the measured solar radiation data were analyzed. The electricity generation capacity was calculated by using the Ripasso Dish Stirling characteristics concerning the radiation data. After obtaining the electrical capacities, the PEM electrolyzer and compressor that can be operated have been selected. A PEM electrolyzer of 4480 W and a hydrogen compressor of 2.3 kW were selected. With the isontropic compressor power calculation it is found out that the selected compressor suits with the required power. For storage, a 300L & 200 bar pressure hydrogen tanks with type 2 features were selected.

The constructed system operates following the offsetting strategy. When radiation levels are low, the produced electricity is fed to the grid. The electrolyzer has a maximum operating time of 10 hours per day. The Solar Dish system requires 50 W/m^2 of solar energy to function. When there is enough radiation, the system feeds the electrolyzer directly. By operating 3335 hours per year, a solar Stirling dish generates 47950.3 kWh of electricity. By working 3021 hours per year, a PEM electrolyzer can produce 376.99 kg of hydrogen per year. After 10 hours, the volume of hydrogen generated, at 200 bars, was determined to be 70 L in Ideal gas equation and 76.93 L according to Van der Waals equation. There is a 10% difference between these approaches in these conditions. The tank capacity chosen can hold 4.843 kg of hydrogen and can be filled 77 times per year. If the 377 kg H_2 produced was produced with the steam reforming method, 2639 kg of CO_2 would be emitted. Overall efficiency of the system for hydrogen storage is 21%.

According to IRENA values [80], LCOE values of concentrated solar power from 2010 to 2011 dropped by 68% to 0.144 $/kWh. However, this statistic does not include Solar Stirling dish systems. In our study LCOE value was found to be 0.45 $/kWh. According to the statistics from EIA [81] coal has an LCOE value 73.86$/MWh which converted to kW, concentrated Solar Dish Stirling is way above the value.

In conclusion, the modeling of Solar Dish Stirling for green hydrogen Production in the Ankara region is viable with the offset strategy. Looking out for the future, this system appears to be promising. Its great efficiency and environmentally friendly technology are essential for the future of our planet. Due to the advancement of technology and the growing popularity of the system, production costs will reduce, and installation numbers will increase.

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