

التقييمات الحرارية والاقتصادية للهيدروجين الأخضر في ليبيا
باستخدام الألواح الكهروضوئية الشمسية وجهاز التحليل الكهربائي
الكهروضوئي والبوليمر الانعكاسي



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Thermoeconomic Assessments of Green Hydrogen in Libya
Using Solar Photovoltaics (PV) Panels and PV&PEM Electrolyzer

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قال الله تعالى :

بسم الله الرحمن الرحيم

﴿اللَّهُ الَّذِي خَلَقَ السَّمَاوَاتِ وَالْأَرْضَ وَأَنْزَلَ مِنَ السَّمَاءِ مَاءً فَأَخْرَجَ بِهِ مِنَ الثَّمَرَاتِ رِزْقًا لَّكُمْ ۖ وَسَخَّرَ

لَكُمْ الْفُلْكَ لِتَجْرِيَ فِي الْبَحْرِ بِأَمْرِهِ ۚ وَسَخَّرَ لَكُمْ الْأَنْهَارَ ۖ

صدق الله العظيم

سورة إبراهيم، الآية 32

الاهداء

إلى والدي أطال الله في عمره وأمدّه بالصحة والعافية

وإلى والدتي رحمها الله وغفر لها وأسكنها فسيح جناته

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المستخلص:

يمثل الإشعاع الشمسي الوفير في ليبيا فرصة رئيسية للاستفادة من مصادر الطاقة المتجددة لإنتاج الهيدروجين بكميات اقتصادية ، في هذه الدراسة تم تقييم الهيدروجين الأخضر في ليبيا باستخدام الألواح الكهروضوئية وجهاز التحليل الكهربائي الكهروضوئي والبوليمر الانعكاسي بعد اتضاح جدوى وفوائد إنتاج الهيدروجين الأخضر في ليبيا من خلال استخدام الألواح الشمسية الكهروضوئية.

في هذه الدراسة تم الأخذ في الاعتبار عدة عوامل حرارية واقتصادية، فزيادة الحرارة تزيد من كفاءة إنتاج الهيدروجين عبر الألواح الكهروضوئية ، كما ان دمج مراوح التبريد أو البوليمرات الانعكاسية يساعد بفعالية في تقليل الآثار السلبية حيث يوفر دمج أنظمة الطاقة الشمسية مع خلايا التحليل الكهربائي الكهروضوئي مصادر طاقة نظيفة لإنتاج الهيدروجين، مما يساهم في خفض انبعاثات الكربون ، كما أن التحديات الاقتصادية تشمل تكلفة البوليمرات والتحليل الكهربائي، بالإضافة إلى توفر الكهرباء النظيفة والعمالة الماهرة، مع الأخذ في الاعتبار الاستفادة من الإشعاع الشمسي الغزير في ليبيا .

التقييمات الحرارية بالدراسة شملت التبريد وتأثيره على الألواح الكهروضوئية حيث يؤدي ارتفاع درجة الحرارة إلى انخفاض كفاءة الألواح الكهروضوئية وتناقص الطاقة المنتجة فتم استخدام البوليمرات الانعكاسية لتعكس أشعة الشمس بعيداً عن الألواح، مما يساهم في تبريدها ورفع كفاءتها، وبالتالي زيادة إنتاج الهيدروجين الأخضر .

التقييمات الاقتصادية بالدراسة شملت تكلفة تقنية التحليل الكهربائي حيث تعتمد الجدوى الاقتصادية على تكلفة تقنية التحليل الكهربائي والبوليمرات الانعكاسية، بالإضافة إلى كفاءة النظام . كما شملت الدراسة طريقة التعامل مع المشاكل التقنية المتمثلة في درجة حرارة الألواح وفعالية البوليمرات، ودمجها مع أنظمة التحليل الكهربائي بالإضافة الى تطوير البنية التحتية لتخزين الهيدروجين الأخضر ونقله بشكل آمن. وهو ما يشكل تحدياً اقتصادياً كبيراً .

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Abstract:

Libya's abundant solar radiation represents a major opportunity to leverage renewable energy sources to produce hydrogen in economic quantities. This study evaluated green hydrogen production in Libya using photovoltaic panels, a photoelectrolyzer, and a reflective polymer. This study demonstrated the feasibility and benefits of producing green hydrogen in Libya using photovoltaic solar panels. This study considered several thermal and economic factors. Increasing heat increases the efficiency of hydrogen production using photovoltaic panels, while integrating cooling fans or reflective polymers effectively helps reduce the negative impacts. Combining solar systems with photovoltaic electrolyzers provides clean energy sources for hydrogen production, contributing to a reduction in carbon emissions. Economic challenges include the cost of polymers and electrolyzers, as well as the availability of clean electricity and skilled labor, taking into account the benefits of abundant solar radiation in Libya. The study's thermal assessments included cooling and its impact on photovoltaic panels. High temperatures lead to a decrease in photovoltaic panel efficiency and a decrease in energy production. Reflective polymers were used to reflect sunlight away from the panels, contributing to cooling and increasing their efficiency, thus increasing green hydrogen production. The study's economic assessments included the cost of electrolysis technology, as economic feasibility depends on the cost of electrolysis technology and reflective polymers, in addition to the efficiency of the system. The study also addressed technical issues related to panel temperature and polymer efficiency, integrating them with electrolysis systems, and developing infrastructure for safe green hydrogen storage and transport, which poses a significant economic challenge.

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List of Abbreviation

AC	ALTERNATING CURRENT
AEL	ALKALINE ELECTROLYSER
AEP	ANNUAL ENERGY PRODUCTION
E_g	BAND GAP ENERGY
BOS	BALANCE OF SYSTEM
TWh	TERA WATT HOUR
E_{ph}	PHOTON ENERGY
PSH	PEAK SUN HOURS
CO_{2e}	CARBON DIOXIDE EMISSIONS EQUIVALENT
(CCS)	CARBON CAPTURE AND STORAGE
CAPEX	A CAPITAL EXPENDITURE
DC	DIRECT CURRENT
BOS	BALANCE OF SYSTEM
GHG	GREEN HOUSE GAS
H_{2s}	HYDROGEN STORAGE
HSP	HYDROGEN CARBON SAVINGS PRICE
HHV	HIGHER HEATING VALUE
HSC	HYDROGEN STORAGE COST
HSP	HYDROGEN SELLING PRICE.
NOCT	NOMINAL OPERATING CELL TEMPERATURE OF THE PANEL.
IEA	INTERNATIONAL ENERGY AGENCY
PEM	MEMBRANE ELECTRODE ASSEMBLYS
PEMFC	PROTON EXCHANGE MEMBRANE FULE CELL
PV	PHOTOVOLTAIC PANEL
(BEV)	BATTERY ELECTRIC VEHICLES

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(FCEV)	FUEL CELL ELECTRIC VEHICLES
AE L	ALKALINE ELECTROLYSER
SOEL	SOLID OXIDE ELECTROLYSE
(S2H)	SOLAR-TO-HYDROGEN
(SPE)	SOLID POLYMER ELECTROLYTE (SPE) WATER
PEMEC	PROTON EXCHANGE MEMBRANES FOR POLYMER ELECTROLYTE FUEL.
DI water.	DEIONIZED WATER, OR DI WATER.
SYMBOLS	
A	AREA
C	ELECTRICITY COST (€/KWH
Cp	POWER COEFFICIENT
C	CONCENTRATION (MOL/M ³
E	ENERGY/ ELECTRICITY DISPATCH (KWH
E0	STANDARD CELL POTENTIAL
F	FARADAY CONSTANT (96485 C/MOL)
H	HYDROGEN
Ht	HYDROGEN PRODUCTION TARGET (KG)
i	CURRENT DENSITY (A/CM ²)
mH2	HYDROGEN MASS FLOW RATE
N	SYSTEM LIFE TIME

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<i>O</i>	OXYGEN
<i>P</i>	GENERATED POWER (KW)
<i>P f</i>	PENALTY FUNCTION
<i>R</i>	RESISTANCE (Ω)
<i>OCV</i>	OPEN CIRCUIT VOLTAGE
<i>R</i>	GAS CONSTANT (8.3145 J/MOLK)
<i>T</i>	TEMPERATURE (K)
<i>V</i>	VOLTAGE
<i>Z</i>	NUMBER OF ELECTRONS TRANSFERRED PER REACTION
<i>Hreac</i>	ENTHALPY CHANGES OF REACTION
<i>$\Delta Greac$</i>	CHANGE IN GIBBS FREE OF REACTION J/MOL
<i>ΔHo</i>	CHANGEIN ENTHALPY
<i>ΔGo</i>	INTERNAL ENERGY OF THE SYSTEM
<i>$\Delta Sreac$</i>	ENTROPY CHANGES OF REACTION J/MOLK
<i>$V\Delta H$</i>	ENTHALPY VOLTAGE
<i>V_{cell}</i>	CELL VOLTAGE
<i>V_{ohm}</i>	OVERVOLTAGE DUE TO OHMIC LOSSES
<i>V_{act}</i>	ACTIVATION OVERVOLTAGE
<i>V_{con}</i>	CONCENTRATION OVERVOLTAGE
<i>V_{MPP}</i>	MAXIMUM POWER POINT VOLTAGE
<i>V_M</i>	VOLTAGE OF ELECTROLYSIS MODULE.
<i>$I-V$</i>	CURRENT-VOLTAGE (CURVE).
<i>HTO</i>	HYDROGEN-TO-OXYGEN
GREEK SYMBOLS SUBSCRIPTS	
<i>o</i>	REFERENCE VALUE

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A	ANODE
C	CATHODE
ELe	ELECTROLYSER
e1	LECTROLYSER UNIT 1
e2	ELECTROLYSER UNIT 2
g	GRID
T	TIME IN HOUR

CHAPTER 1

1. Introduction:

The planet is warming up. The production of energy by burning fossil fuels has been the primary source of carbon dioxide (CO₂) emissions for hundreds of years. Water vapor and CO₂ are the greenhouse gases mainly responsible for global warming. Global temperatures have continuously risen during the last century. The increasing levels of carbon dioxide concentration in the atmosphere is one of the biggest challenges modern societies is facing. Population growth, intensive agriculture, deforestation and increase in worldwide energy use are some of the causes for CO₂ rise concentrations. Further, higher CO₂ levels mean higher global temperature, melting glaciers, rising sea levels and more extreme weather events. Many countries support the initiative to an energy transition by implementing policies, and ambitious programs towards a CO₂ reduction. Producing energy from renewable sources is an efficient way to reduce CO₂ emissions. The world faces a revolution in energy systems as it seeks to keep up with the increase in energy demand while simultaneously reducing greenhouse gas emissions. Solar photovoltaic (PV) has established itself as a cost competitive green alternative for fossil fuels but since it is inherently intermittent, securing a reliable energy supply is a challenge. To overcome this challenge cost effective storage solutions become increasingly important. Green hydrogen is energy, the efficiency of the electrolysis process, the availability and cost of water, and the demand for hydrogen. The cost of renewable energy is a particularly important factor, as it typically accounts for a form of hydrogen produced through the electrolysis of water, using renewable energy sources such as wind, solar, or hydropower. Unlike traditional hydrogen production methods, which rely on fossil fuels, green hydrogen is considered a clean and sustainable source of energy that can help reduce greenhouse gas emissions and Combat climate change. In the energy systems of the future, solar energy will be the predominant energy source. However, the growth in solar power brings new technical challenges to overcome. Power intermittency, grid flexibility, and surplus electricity are just a few of the challenges that must be addressed for the power systems of the future.

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The technology used to produce green hydrogen is called electrolysis, which involves passing an electric current through water to separate it into its constituent parts, hydrogen and oxygen. The electrolysis process can be carried out using various types of electrolyzers, including alkaline, proton exchange membrane (PEM), and solid oxide electrolyzers. Each type of electrolyzer has its own advantages and disadvantages, and the choice of electrolyzer depends on factors such as cost, efficiency, and scalability.

Green hydrogen is a form of hydrogen produced through the electrolysis of water, using renewable energy sources such as wind, solar, or Hydropower. Unlike traditional hydrogen production methods, which rely on fossil fuels, green hydrogen is considered a clean and sustainable source of energy that can help reduce greenhouse gas emissions and combat climate change.

In the energy systems of the future, solar energy will be the predominant energy source. However, the growth in solar power brings new technical challenges to overcome. Power intermittency, grid flexibility, and surplus electricity are just a few of the challenges that must be addressed for the power systems of the future.

Several factors affect the production of green hydrogen, including the availability and cost of renewable majority of the cost of green hydrogen production. As the cost of renewable energy continues to decline, the cost of green hydrogen is also expected to decrease.

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The rate of hydrogen production worldwide is currently relatively low, as the vast majority of hydrogen produced today comes from fossil fuels.

However, the demand for green hydrogen is expected to increase in the coming years as countries and companies seek to reduce their greenhouse gas emissions and transition to more sustainable energy sources. According to a report by the International Energy Agency (IEA),

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global hydrogen production could increase tenfold by 2050, with green hydrogen accounting for a significant share of this increase.

Regarding Libya, there is limited information available on the country's involvement in green hydrogen production. However, given Libya's abundant solar and wind resources, it has the potential to become a significant producer of green hydrogen in the future. Previous studies have focused on Libya's potential for renewable energy development, including solar and wind power, but more research is needed to determine the feasibility and potential of green hydrogen production in the country. In recent years, there has been growing interest in green hydrogen as a potential solution to some of the world's most pressing energy and environmental challenges. One of the main advantages of green hydrogen is its ability to be stored and transported, making it a versatile energy carrier that can be used for a variety of applications, such as fuel for transportation, heating and electricity generation.

However, there are still several challenges to overcome before green hydrogen can become a mainstream energy source. One of the biggest challenges is the high cost of green hydrogen production compared to fossil fuel-based hydrogen. The cost of renewable energy, such as wind and solar, is still relatively high, and the electrolysis process used to produce green hydrogen is also relatively expensive. In order for green hydrogen to become cost-competitive with fossil fuel-based hydrogen, the cost of renewable energy needs to continue to decline, and there needs to be further innovation and improvements in electrolysis Technology.

Another challenge is the lack of infrastructure for storing and transporting green hydrogen. The existing infrastructure for fossil fuel-based hydrogen is not compatible with green hydrogen, as it requires different equipment and safety protocols. Therefore, significant investments will be needed to build a new green hydrogen infrastructure, including pipelines, storage facilities, and fueling stations.

Solar photovoltaic (PV) has established itself as a cost competitive green alternative for fossil fuels but since it is inherently intermittent, securing a reliable energy supply is a challenge.

In terms of Libya, the country has significant potential for renewable energy development, particularly in the form of solar and wind power. However, the country has been facing significant political and economic instability in recent years,

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which has hindered its ability to develop its energy sector. Nevertheless, there are opportunities for international partnerships and investments to support Libya's renewable energy development, including the production of green hydrogen. development, including the production of green hydrogen.

The Potential for Green Hydrogen in Libya: is expected to play a key role as an emission-free energy carrier in future energy systems of the globe. Speedily dropping costs of green energy have increased the competitiveness and market share for green energy. As green energy becomes cheaper, “Green hydrogen” made with wind and solar electricity could become the cheapest. As a result, hydrogen will have a huge role to play in decarbonizing the global economy, especially in hard-to-decarbonize sectors. Today Hydrogen is believed to have the potential to become one of the major energy carriers of the 21st century to become the "new oil" or the "new natural gas".

Officially the State of Libya, is a country in the Maghreb region in North Africa bordered by the Mediterranean Sea to the north, a gateway to Africa and Southern Europe, a country has the advantage of having plenty of space 1.76 million Km², sunshine. the potential to become a renewable energy giant according to Responding to Climate Change. It boasts a very high daily solar radiation rate — on a flat coastal plain it is about 7.1 (kWh/m²/day) and in the south region it is about 8.1kWh/m²/day. ^[1] with an annual average solar greater than “3500” hours . The ‘Libyan Renewable Energy Authority’ has estimated that the average solar sunlight hours are approximately “3200” hours/year and that the average solar radiation is 6 kWh/m²/day. Therefore, renewable energy could provide a good complement for meeting peak loads; and this, in turn, may be a reasonable reason to encourage Libya's government to invest in solar projects. Libya has the potential to supply all of its own electricity needs and an exportable, significant part of its neighbor’s needs from the renewable energy resources available in this oil rich country.^[2]

If you compare the UK to Libya, Great Britain has less than half that amount at about 2.95kWh/m²/day.

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For what concern the water resources, very large quantities of fresh water are available in the Libyan desert. Indeed, 250000 km² of the north-Western-Sahara-Aquifer-System-(NWSAS) are in Libya. Another groundwater layer located in this country is the Nubian Sandstone Aquifer System (NSAS), which covers the land area in south-eastern Libya. From this fossil aquifer, the largest irrigation project in the world, known as the Great Man-Made River, supplies water to the Sahara in Libya, extracting roughly 2.4 km³ per year.^[2]

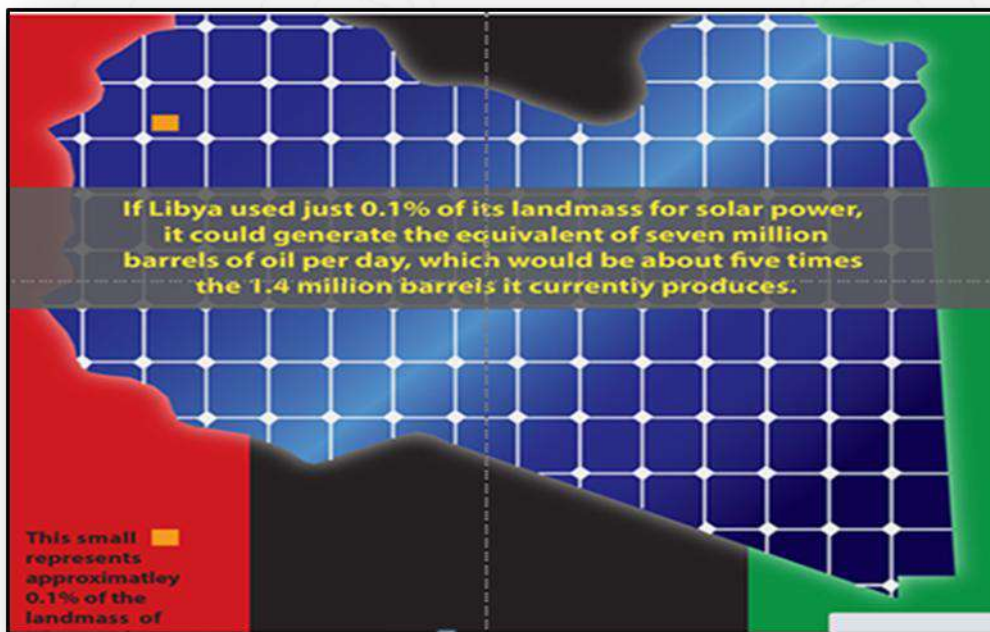


Fig. (1.1) Libya Solar Potential 5x Larger Than Oil Reserves.

The place that has been selected in Libya to perform the simulations is the region of ZLITEN, is one of the most remote and the most deprived regions in Libyan coast. The development of this region requires the exploitation of its natural resources more particularly of its solar energy and the abundance of groundwater resources. However, the exploitation in an effective and viable way of these huge natural resources requires the conversion of these sources of energy into an energy vector that is versatile in its use, storable, transportable and ecologically acceptable. Solar hydrogen seems to be the best candidate today.

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Fig. (1.2) high groundwater levels in the city of ZLITEN.

1.2. Research Work on Solar-to-Hydrogen Systems:

Several studies to assess the feasibility of implementing hydrogen production via electrolysis using solar power have been carried out recently.

Hydrogen energy is very flexible, as it can be used as a gas or a liquid, converted into electricity or fuel, and produced in a number of different ways. Hydrogen gas was first produced artificially back in the 16th century, while the first fuel cells and electrolyzers were made in the 19th century (“The green hydrogen revolution has started, and it won’t be topped,2018). The first reference we have found to the term green or renewable hydrogen was mentioned by National Renewable Energy Laboratory in 1995, who used the term renewable hydrogen (hydrogen produced from renewables) as a synonym for green. The State of California defined green hydrogen as being produced cleanly and sustainably, using a renewable source such as solar or wind. The first mention of green hydrogen in EU policy documents is the declaration for establishing a green hydrogen economy in Europe in 2007 (Velazquez Abad and Dodds, 2020). Research Work on Solar-to-Hydrogen Systems.

A small demonstration project developed by Clarke et al. ^[3] shows a method to integrate PV modules with a PEM electrolyzer directly. The system uses a 2.4 kW PV array connected directly with a PEM electrolyzer.

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The study points out the advantage of a direct coupling configuration is the cost reduction of a DC-DC converter and power electronics. However, when comparing the cost of components, the most expensive ones are related to the electrolyzer stack. The PV technology and the balance of its related components are becoming cheaper. Hence, the saving in power electronics does not balance out the costs of operation time in the electrolyzer. After approximately four months of operation, the electrolyzer stopped running due to a degradation of its membrane.

Many previous researches focused on using solar energy to produce hydrogen, including: in 1983, a solar station was built in Belgium to produce hydrogen for the purpose of the storing energy and- to gain practical experience in constructions solar systems that operate in difficult constructing such as foggy northern regions or acclimate polluted by industrial ^[4]. In 1994, researchers Walt Bailey and others in the United States built a home system to produce hydrogen from water and solar radiation energy to use it as a resource to store inexhaustible backup energy during daylight hours and invest it to produce thermal and electrical energy when needed ^[5]. In 2001, Honda completed At the Research and Development center in Torrance, California, building research station for the processing and production of hydrogen, that relies on solar energy for purpose of conducting studies on the production, storage and processing of hydrogen by exploiting inexhaustible energy sources and contributing to supporting and assigning programs to develop cars that operate with a fuel cell and hydrogen gas.,

In another study performed by Homayoun *et al.* ^[6] a chemical assessment and sizing of a standalone hybrid power system combining PV panels, batteries, and hydrogen storage is presented. An optimization framework model is developed to determine the optimum component sizes based on the lowest net present cost while maintaining the system reliability. By using this framework, the study concludes that the most cost-effective alternative to the energy storage is a combination of batteries with hydrogen technology. Additionally, this work concludes that the system design and sizing have an important effect on its initial cost. However, no designing rules for hybrid power systems are presented. Neither, the impact of irradiance levels or the electrolyzer operational parameters is discussed in this work.

A system performance analysis is presented, but the results do not discuss the impacts of the electrolyzer switching on/off cycles due to the intermittency nature of the PV system. Summarizing, design, operation, and system performance are three crucial topics when using solar-to-hydrogen systems. The goal of such a system is to produce hydrogen in the most cost-effective conditions while mitigating the intermittent character of solar energy. It has been demonstrated that hybrid power systems work very well for grid-tied configurations. However, there are extra optimization challenges, for a self-sufficient energy system, when the system operates off-grid. A more robust energy storage unit and a fine energy control management are needed to compensate the system instability. Overall, hydrogen production from electrolysis using solar power is a promising solution, but there are some challenges which need to be tackled. Thus, both a detailed and more comprehensive knowledge of the system integration is necessary.

1.3. Research Questions:

The primary objective of this research is to gain fundamental insights into the promising process for hydrogen production using solar power. A second objective is to provide some general design rules of a solar-to hydrogen system, along with the performance assessment of each component and the whole operation of the system. Literature review shows that there is a limiting knowledge about the sizing of each of the components in a solar-to-hydrogen system and also for the assessment of its performance. There is a need to understand how the solar-to-hydrogen system performs and what critical parameters need to be considered when designing such a system. Consequently, power suppliers, engineers, and students would benefit from a more profound knowledge of the specific operation and limitations of a solar-to-hydrogen system. Thus, the central research question of this study is:

How to gain fundamental understanding in the design, operation, and assessment of a system for green hydrogen production in Libya via PEM electrolysis using solar panels?

1.4. Problem Statement:

Libya, endowed with abundant solar irradiation, stands poised to harness solar photovoltaic (PV) technology for green hydrogen production, yet faces significant challenges in realizing this potential. Key issues include the lack of infrastructure for renewable energy integration, insufficient investment in clean energy projects, and regulatory frameworks that do not adequately support green hydrogen initiatives.

Despite ample sunlight, Libya's energy landscape remains dominated by fossil fuels, perpetuating environmental degradation and economic instability. The absence of a robust renewable energy infrastructure hinders the scalability of solar PV systems for hydrogen production, limiting their widespread adoption.

Additionally, the investment climate in Libya is characterized by political volatility and uncertainty, deterring potential investors from committing to long-term renewable energy projects. Without substantial investment and financial incentives, the development of green hydrogen production facilities using solar PV technology remains constrained.

Furthermore, regulatory frameworks governing energy production and distribution in Libya do not sufficiently incentivize or facilitate the transition to green hydrogen. Ambiguous policies and bureaucratic hurdles impede progress, hindering the development of a conducive environment for renewable energy projects.

Moreover, technical challenges such as intermittency of solar power and the efficiency of electrolysis processes pose significant obstacles to the reliable and cost-effective production of green hydrogen using solar PV panels.

In summary, the problem statement underscores the urgent need to address infrastructure deficiencies, attract investment, reform regulatory frameworks, and overcome technical barriers to unlock Libya's potential for green hydrogen production using solar photovoltaics. Only by tackling these challenges can Libya transition towards a sustainable energy future while capitalizing on its abundant solar resources.

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1.5. Methodology:

The hydrogen production systems considered in this study are composed of electrolyzers directly powered by solar PV plants, without connection to the local electric grid. Thus, hydrogen is solely produced from a renewable resource and therefore very low GHG emissions are involved. PV technology has been selected as their related costs have experienced sharp reductions in the last years. Moreover, this trend is set to continue over the next years.

1.6. Thesis Outline:

The contents of this master thesis are structured as follows:

Chapter 2:

In this chapter We will give a simplified idea about the source of solar energy. And we tried to clarify general idea about hydrogen, its sources in nature, its role in life, methods of transporting and storing it. its properties, tis most important application in life, and methods of producing it.

Chapter 3:

This chapter starts introducing the basics concepts of solar cells and its operational principles. Next. next we explained general idea about solar panel technology, its types, manufacturing methods, advantages and disadvantages.

Chapter 4:

Photovoltaic performance, environmental factors, electrical characteristics and how it connected.

Chapter 5:

This section deals with the fundamental electrochemistry and thermodynamic concepts of water electrolysis are introduced. Then, the hydrogen production using solar electricity is presented. Additionally. The PEM efficiency, an analysis of the three main electrolysis technologies namely alkaline, polymer electrolyte membrane and solid oxide electrolyte are discussed. Main features of current commercially available electrolyzers are also investigated.

Chapter 6:

This chapter presents the simulation of a solar-to-hydrogen (*S2H*) system. Each component in the system is simulated separately, based on a model that describes the physical and chemical principles of the individual component. The model is written in the mathematical tool Matlab Simulink, and structured on three different modules: the photovoltaic module as a primary energy source; the water PEM Electrolyzer as a hydrogen generator; the gas storage tank acting as a sink for the generated hydrogen.

Finally, Chapter 6 closes with the concluding results generated by this study, thus answering the central research question.

CHAPTER 2

2.1. Introduction:

In this chapter We will give a simplified idea about the source of solar energy. And we tried to clarify general idea about hydrogen, its sources in nature, its role in life, methods of transporting and storing it. its properties, tis most important application in life, and methods of producing it.

2.2. The source of solar energy:

The source of solar energy The Sun, our closest star, is a spherical gaseous self-gravitating body consisting mainly of hydrogen. It is located at the center of the solar system, on average 1.5×10^{11} m from Earth. At the inner core of the Sun, the gravitational force creates a pressure which generates nuclear fusion that turns hydrogen into helium. In this process a portion of the mass is converted into an abundant amount of electromagnetic radiation, which makes the Sun the dominant source of radiative energy in the solar system. The Sun has a complex physical structure and consists of several regions, from the dense inner core to the outer atmospherically layer, the corona. Both the corona and the core are very hot, in the order of $10^6 - 10^7$ K, while the intermediate regions that transport and emit energy as outgoing radiation are cooler (although hot by earthly standards). Energy from fusion reactions in the Sun's interior is transported through successive convection, radiation, absorption, emission and reradiation to the Sun's equivalent of a surface, the photosphere, which absorbs and emits a continuous spectrum of radiation. The photosphere is the source of most visible radiation reaching Earth. It has a surface temperature, or, more correctly, an effective black-body temperature of 5777 K (this is the temperature of a black-body radiating the same amount of energy as the Sun). Although it consists of several absorbing and emitting layers and has a considerable temperature gradient across its radius, the Sun closely resembles the ideal concept of a black-body.

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2.3. Hydrogen:

Table. (2.1) periodic table.

Hydrogen

Hydrogen is a chemical element with symbol H and atomic number 1. Classified as a nonmetal, hydrogen is a gas at room temperature.

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
		*	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
		**	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Hydrogen is the most important element in the universe. Many of planets and all stars are basically consist of hydrogen. But on the earth, the hydrogen is rarely found as a free gas. The atmosphere contains a very little amounts of it "0.07 percent". It is usually mixed with other natural gases in crustal reservoirs. However, it has been discovered in a large amount in few wells. The principle of hydrogen energy production covered a whole array of methods, such as electrolysis, thermal photolysis, and thermo chemical cycles ^[7]. Hydrogen energy one of most important source for Renewable energy. Many searches studied method of Hydrogen preparing. Because of that the Hydrogen is most spread in the universe, it is rarely found as a pure element in the nature ^[8]. But it is available as a compound. The water compound is most spread, therefore the water considered as an important and suitable for renewable energy. The hydrogen is used as a fuel for space crafts, water heating, and for cooking. It is more convenient to produce hydrogen by electrolysis using excess electricity and conversion efficient ranging from (80-95%) are achievable ^[9]. A theoretical and experimental studies was done about using solar thermal to produce hydrogen ^[10,11].

Hydrogen is known to be the smallest element in the periodic table and is available easily see Figure (2.4). Whenever Hydrogen is in the making process, it always combines itself with the identical carbon-free molecule. Green Hydrogen is produced by breaking apart H_2 and Oxygen while using electricity. This process is known as Electrolysis. Also, Green Hydrogen can be created without releasing harmful greenhouse gases and is known to be the clean Hydrogen. Even though it is a colorless gas yet, it has numerous color codes, i.e., because these are color codes or nicknames given to the gas in various industries depending upon its use.

Green hydrogen, also known as renewable hydrogen, will play a vital role in reducing global carbon emissions and help heavy industries move closer to a carbon-neutral future. Global warming is one of the greatest challenges that the world currently faces.

If significant action is not taken to reduce carbon emissions, then we will not be able to prevent climate change and its profound impact on our planet. Perhaps our biggest opportunity to reduce the world's carbon footprint is to switch from fossil fuel sources to renewable energy sources. Green hydrogen is a form of clean energy that will likely facilitate this energy transition to enable the world to move away from heavily polluting non-renewables.

As an energy carrier, hydrogen can be used for a wide array of energy and industrial applications and can be stored for long periods of time in various forms. Hydrogen is already one of the most widely produced industrial gases in the world.

Fuel cell technologies offer a method to generate electricity by combining hydrogen with oxygen in a chemical process. This is typically much more efficient than a combustion process, while also being considerably quieter and producing zero carbon emissions (if pure hydrogen) or zero nitrogen oxide emissions when using hydrocarbon fuels. When hydrogen reacts in a fuel cell to generate electricity, the only products are electricity, a small amount of heat, and water. Approximately, 42 kilograms of hydrogen are needed to produce 1 megawatt-hour of electricity using a fuel cell of 60 percent efficiency^[10]

Hydrogen's specific energy is the highest among conventional fuels, but its energy density is the lowest, so pressurization or liquefaction is required for hydrogen to be used as a fuel. These fundamental characteristics of hydrogen are the primary drivers of its value as a fuel.

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Hydrogen is a secondary form of energy, produced using other primary energy sources, such as natural gas, coal, or solar technologies. More than 8 million tons of hydrogen are consumed in the United States each year, primarily by the chemical and petroleum industries^[10]

2.3.1. Where we can find hydrogen in nature?

Nuclear fusion in the Sun.

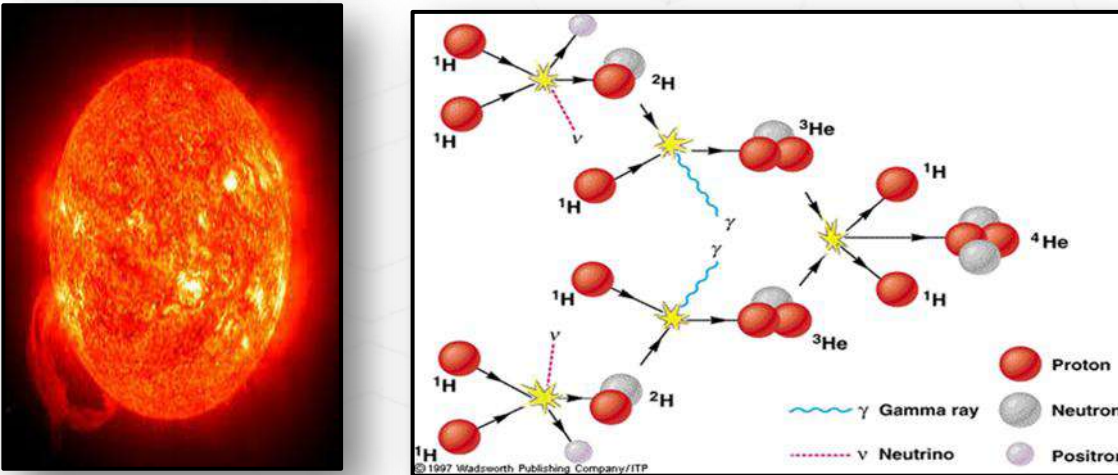


Fig (2.1).

Hydrogen fuses by the proton - proton chain.

How does nuclear fusion occur in the Sun?

The core starts from the center and extends outward to encompass 25 percent of the sun's radius Figure (2.2).

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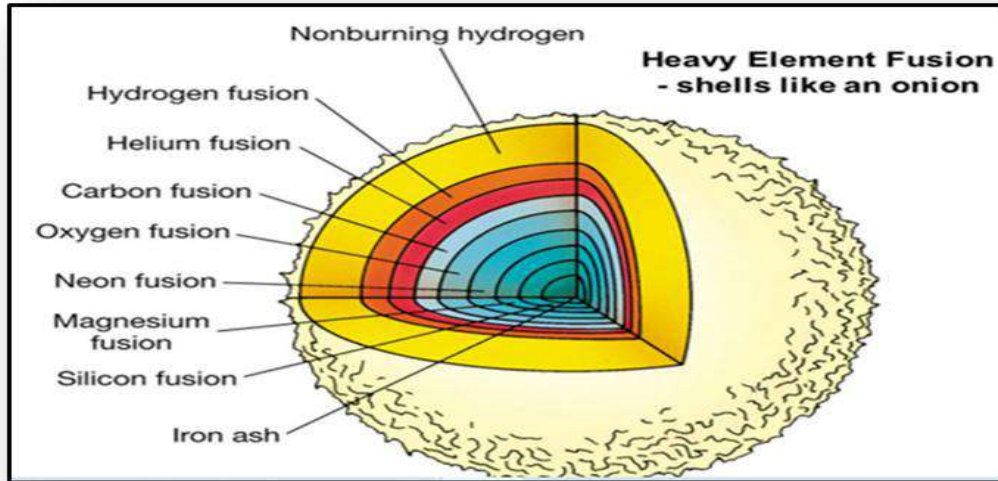


Fig. (2.2). Illustration of the structure of the sun. At the sun's core hydrogen atoms undergo nuclear fusion, producing helium atoms and releasing heat and light energy as photons.

Its temperature is greater than 15 million degrees Kelvin At the core, gravity pulls all of the mass inward and creates an intense pressure. The pressure is high enough to force atoms of hydrogen to come together in nuclear fusion reactions something we try to emulate here on Earth. Two atoms of hydrogen are combined to create helium-4 and energy in Several steps.

Fusion of hydrogen into helium, which occurs via proton chain. As shows in Figure (2.1), (2.3).

Gravitational equilibrium acts as a thermostat that keeps the fusion rate steady.

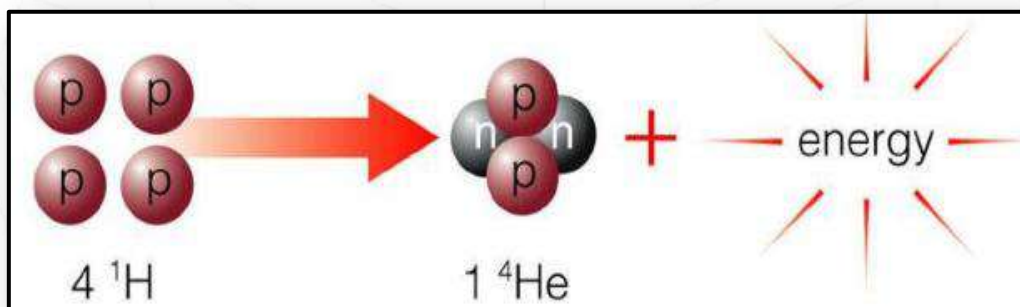


Fig. (2.3). Proton chain.

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When stars exhaust their hydrogen fuel, the resulting helium will start to fuse into heavier elements creating a series of shells all the way up to the most stable element, iron! The Sun produces energy through nuclear fusion by a set of reactions known as the proton-proton chain. From hydrogen to helium in three steps.

- In the first stage two protons combine and one of them converts into a neutron to form a nucleus of the heavy isotope of hydrogen known as deuterium.
- Next, the deuterium nucleus combines with another proton to form the light helium isotope known as helium-3.
- Finally, two helium-3 nuclei combine to form helium-4, releasing two protons.

2.3.2. Energy release:

Overall, four protons are converted into one helium nucleus. Energy is released because the helium nucleus has slightly less mass than the original four protons. The difference in mass is released as energy, in the form of gamma ray photons. The total amount of energy released for each conversion of four hydrogen nuclei into a helium nucleus is about 10 million times more than is produced by the chemical reaction when hydrogen combines with oxygen to form water.

2.4. How many types of Hydrogen gases are there?

Hydrogen production is done by separating hydrogen from the other elements in the molecules where it occurs. There mainly three types of hydrogen are present according with sources of production. as in Figure (2.4). Besides green, there are several color types of Hydrogen:

- Blue Hydrogen.
- Grey Hydrogen.
- Turquoise Hydrogen.

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	GREY	BLUE	TURQUOISE	GREEN	PINK	BROWN
	Hydrogen	Hydrogen	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Technology	Steam methane reforming	Steam methane reforming with carbon capture	Pyrolysis	Electrolysis	Electrolysis	Gasification
Source	 Natural gas	 Natural gas	 Natural gas	 Renewable electricity	 Nuclear energy	 Coal

Fig (2.4). Hydrogen colour coding for various manufacturing processes.

Green hydrogen is produced using renewable energy sources such as solar or wind energy, followed by water electrolysis. Grey and brown hydrogen are produced by methane steam reforming and coal gasification, respectively, and when combined with carbon capture and storage, blue hydrogen is produced. Turquoise hydrogen is produced through the pyrolysis of methane, with solid carbon as a by-product.

Blue Hydrogen:

Blue hydrogen is similar to grey hydrogen, except that most of the CO₂ emissions are sequestered (stored in the ground) using carbon capture and storage (CCS).^[12] Capturing and storing the carbon dioxide instead of releasing it into the atmosphere allows blue hydrogen to be a low-carbon fuel. The two main production methods are steam methane reforming and coal gasification, both with carbon capture and storage. Blue hydrogen is a cleaner alternative to grey hydrogen, but is expensive since carbon capture technology is used.^[13]

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Grey Hydrogen: It is known to be one of the most commonly found Hydrogen and is generated by mixing natural and methane using steam reforming ^[14]. During this, there is an emission of black or brown Hydrogen, which is known to be environmentally damaging as both the CO₂ and Carbon monoxide are generated and not captured.

Turquoise Hydrogen: It is new to the hydrogen colour codes and is created using methane pyrolysis to produce solid carbon, also known as carbon black. This by-product has many industrial uses, including car tires, batteries, plastic, and coating application. ^[14]

Green Hydrogen:

What is Green Hydrogen? The term "Green hydrogen" is coined for hydrogen Gas generated using renewable energy (wind and solar Energy) to power electrolysis (splitting) of water. Hydrogen can also be produced by electrolyzing water, which produces only oxygen as a by-product. In an electrolyser, an electric current is used to separate water into hydrogen and oxygen. The pollutant-free hydrogen emitted when electricity is generated using renewable energy sources such as solar or wind is known as green hydrogen. Additionally, green hydrogen has the potential to reduce our reliance on fossil fuels and provide a more sustainable source of energy for the future. One example is the quickly falling cost of green energy attracting rapid interest in the energy sector' ^[15]

In the energy industry, other colours may be used to differentiate between the types of hydrogen. Although grey, blue and green are most common colours, black, brown, red, pink, yellow, turquoise and white exist as colours for molecular hydrogen. ^[16] Figure (2.5) shows the Green H₂ pressure: 100 bar, blue H₂:20bar, turquoise H₂:20 bar comparison of the cost green, blue and turquoise hydrogen production for 2020 and 2050.

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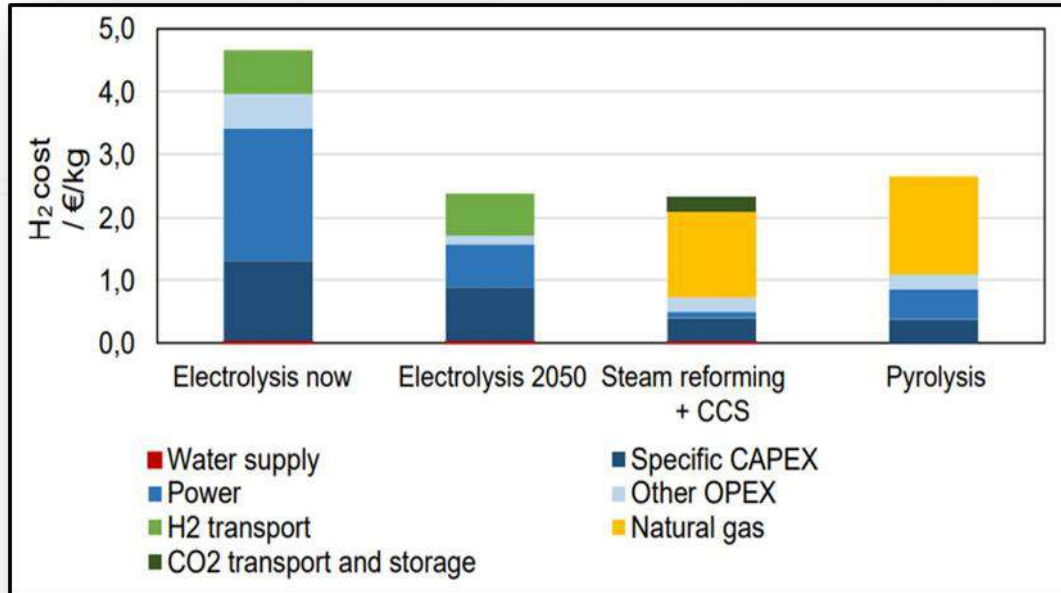


Fig. (2.5) comparison of the cost green, blue and turquoise hydrogen production for 2020 and 2050.

2.5. The Role of Hydrogen:

With the exception of biomass (which can be used to make liquid or gaseous fuels or burned directly to make electricity), the most promising long-term energy sources wind, photovoltaic (PV) cells, solar thermal electric, geothermal, hydro, and nuclear produce only electricity.

Electricity is an ideal energy form for stationary uses in buildings and factories. At the point of use, electrical power can meet consumer needs for heating, cooling, lighting, and powering appliances with essentially no pollution or other serious environmental side effects. There are two circumstances, though, in which renewably generated electricity faces formidable problems. One is in transportation in which lightweight, high energy-density electrical storage systems are still under development.

Without such devices, it will be difficult for electricity to meet most of the nation's ground and air transportation needs. The second problem arises when the electricity is generated from certain solar-electric generators, such as PV cells, or wind machines. Such electricity is, by nature, intermittent and available only when the sun shines or the wind blows. Hydrogen is a leading candidate to solve both of these problems. It provides convenient and affordable energy storage and can be inexpensively converted to electricity or used directly as a fuel. Hydrogen is the lightest and most abundant element in the universe.

It constitutes about 93% of all atoms 4, or three-quarters of the mass of the universe. The element is very reactive chemically and occurs as a free element only in trace amounts. On earth, it is found in water (H_2O), fossil fuels (basically, compounds of hydrogen and carbon), and all plants and animals. Hydrogen gas (H_2) is not a primary fuel in the same sense as natural gas, oil, and coal. No wells produce hydrogen H_2 gas from geologically identified deposits. Rather, hydrogen is an energy carrier, like electricity Hydrogen is a secondary form of energy, produced using other primary energy sources, such as natural gas, coal, or solar technologies. When hydrogen burns, it releases energy as heat and produces water ($2H_2 + O_2 \rightarrow 2H_2O$). No carbon is involved, so using hydrogen produced from renewable or nuclear energy as an energy resource could eliminate carbon monoxide and ozone air pollution and reduce greenhouse warming. (Direct burning of hydrogen may still produce small amounts of nitrogen oxides, however.) Hydrogen and electricity can be considered opposite sides of the same coin. Electricity can be readily used to produce hydrogen via electrolysis. Reversing the process, hydrogen can be consumed to produce pollution-free electricity via a fuel cell. ^[15]

2.6. Hydrogen properties:

Hydrogen is a very light gas, colorless, odorless, and extremely flammable and reacts very easily in the presence of other chemicals. The properties of this gas are summarized in This table.

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Table (2.2) properties of hydrogen, Deuterium and Tritium molecules.

Property	Protium	Deuterium	Tritium
Atomic Hydrogen			
	H	D	T
Atomic mass (<i>amu</i>)	1.008	2.014	3.016
No of electron / protons / neutrons	1 / 1 / 0	1 / 1 / 1	1 / 1 / 2
Nuclear stability	Stable	Stable	Radioactive ($t_{1/2}=12.3$ yrs)
Molecular Hydrogen	H ₂	D ₂	T ₂
Abundance (%)	99.985	0.015	$\sim 10^{-16}$
Molecular mass (<i>amu</i>)	2.016	4.028	6.032
Melting point (K)	13.96	18.73	20.62
Boiling point (K)	20.30	23.67	25.04
Internuclear distance (<i>pm</i>)	74.14	74.14	74.14
Critical Temperature (K)	33.19	38.35	40.60
Enthalpy of dissociation (<i>kJ/mol</i>) [†]	435.9	443.4	446.9

2.7. Renewable Energy Storage:

The largest of the current renewable energy storage projects utilizing hydrogen that are currently in operation are facilities located in Germany at Grapzow ^[17] in the province of Mecklenburg-Vorpommern and in Falkenhagen ^[18] in Brandenburg. Both systems are coupled to a wind farm and utilize electrolyzers

supplied by Hydrogenics and are in collaboration with the utility company E.ON. The 1 MW Grapzow electrolyzer is capable of producing 210 Nm³ of hydrogen per hour. This hydrogen can be directed to either an internal combustion engine to generate electricity or injected into the local gas network.

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The first hydrogen-based system for storing renewable electricity by means of electrolysis and subsequent hydrogen storage was realized in 1991^[19]. Figure (2.6) This project was based in Nuenberg vorm Wald in Germany and marked the beginning of that country's leadership in the adoption and demonstration of technologies essential for realization of hydrogen economy. This pilot plant operated from 1991 to 1999 and utilized electrical power generated from an array of photovoltaic panels with a capacity of 266 kWp (kilowatt-peak).



Fig. (2.6). Overhead view of the Nuenberg vorm Wald Plant [19].

2.8. Methods of distributing and storing green hydrogen:

The storage and distribution of produced hydrogen is associated with technical as well as economic and regulatory barriers. Hydrogen produced from electrolysis becomes 'green' if the process has been powered by renewable sources such as wind or solar power. Alkaline and water electrolysis are the two most prevalent routes for hydrogen production via electrolysis. The hydrogen produced from this process can be stored and converted back to electricity when required see figure (2.7).

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Green hydrogen carries great potential for energy storage because it can be burned when required without any carbon dioxide emissions or used directly in fuel cells. Surplus renewable electricity produced during off-peak periods can power electrolyzer plants to make hydrogen. This hydrogen can then become a store of carbon-free energy converted back to electricity when demands peak and provide balancing power for the grid.

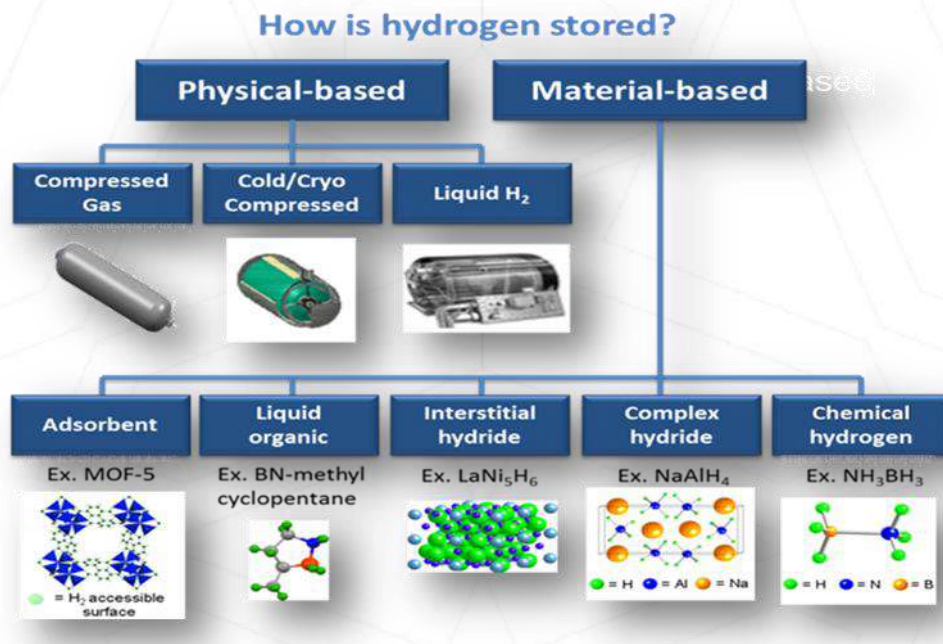


Fig (2.7) Different ways to store hydrogen [(www.Energy.gov.in)]

2.8.1. Compressed gaseous hydrogen:

The common method up until now is compression, which leaves the hydrogen in gas form but reduces storage and transportation costs. Compression to 350 or 700 bars, which is the current standard for the hydrogen used in cars, results in a storage density of more than 40 kg/m³. However, this also takes away approximately 8% of the original energy content. Lower levels of compression, such as 350 bars, requires less energy but leaves a higher volume and may therefore require more investments in storage capacity. For intermediate storage in high-pressure tanks or gas cylinders, pressures of up to 1,000 bar are technically possible. Only special solid steel or steel composite pressure vessels are suitable for high-pressure storage (Adolf *et al.*, 2017)^[20]. Figure (2.8)

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and PV&PEM Electrolyzer.**

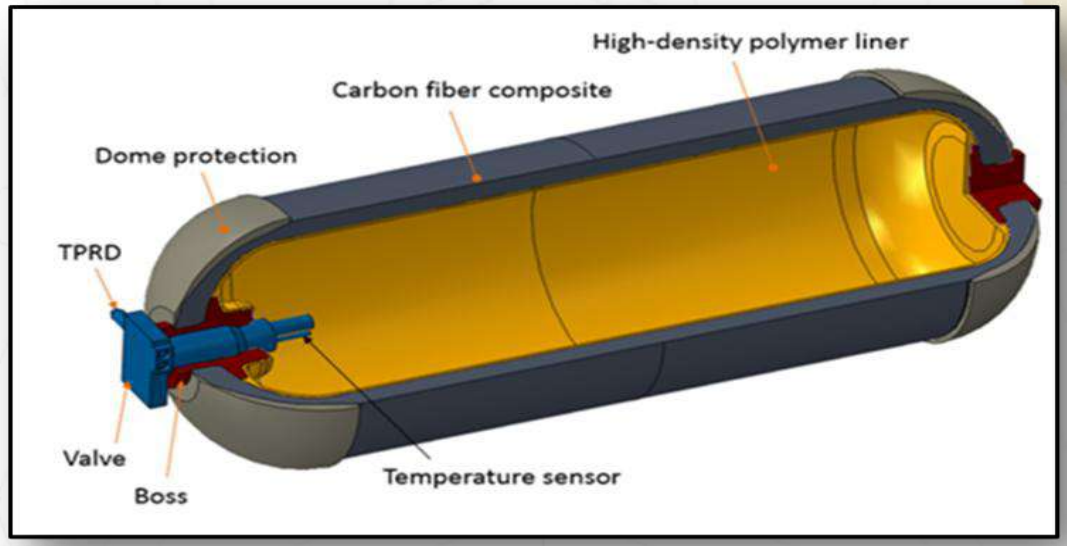


Fig. (2.8) Components of a pressurized hydrogen storage tank.

Compressed gaseous hydrogen may also be stored in underground natural caverns, which presently are used for storage of compressed natural gas. (Blue Move 2017).^[37]

Hydrogen, as a low-flashpoint gas, falls under the legislation for dangerous substances and the regulation on the handling of inflammable, reactive, and pressurized substances, in addition to the equipment and facilities used in the handling of such substances. It is not poisonous, but like LNG, it is associated with high explosion risk and therefore special rules and standards apply, especially if it is stored in volumes of 5 tons or more. This has implications in terms of acceptability as well as costs. Still, Rivard et al. (2019)^[20] note that compressed gas is the most well-established hydrogen storage technology, offering a functional solution for mobility applications.

Hydrogen is normally compressed at ambient temperature and the storage vessels are classified depending on its fabrication materials Figure (2.9).

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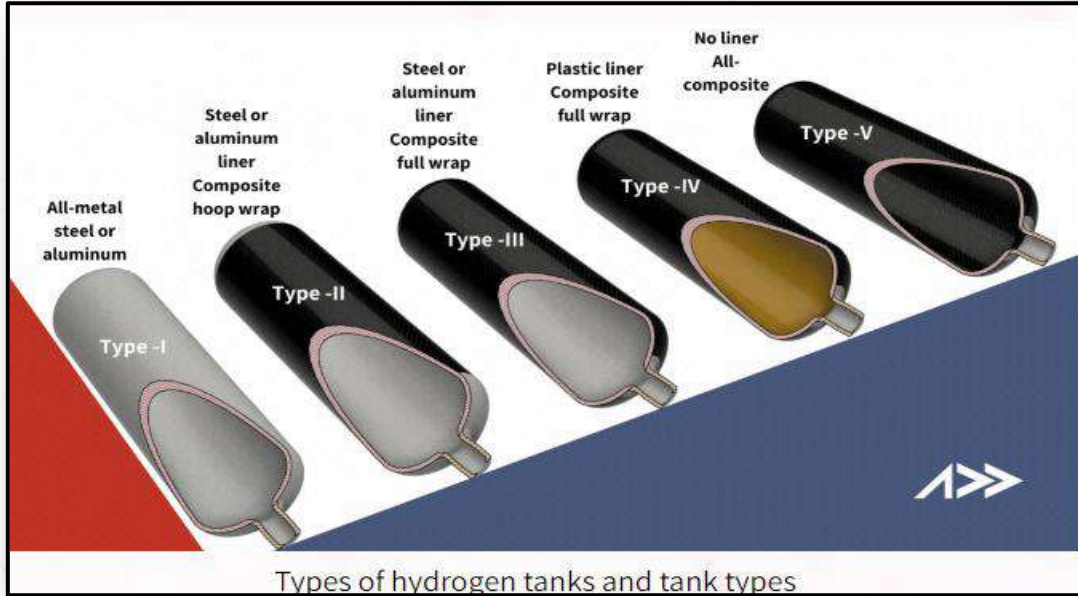


Fig. (2.9). Types of Hydrogen and tank type.

and the maximum pressure allowed as shown in the following table:

Table (2.3). Different types of tanks to store hydrogen^[20]

Tank type	Allowed pressure (bar)	Characteristics
Type I. Steel or Aluminium (seamlessly and without coating)	150-300	Very heavy and with thicker walls. Used mainly in vehicles of natural gas compressed and in stationary industrial applications
Type II. Metallics seamlessly wrapped up in fiberglass and resin	450-800	Very heavy. Used mainly as intermediate tanks for stationary applications
Type III. Seamlessly aluminium coating wrapped up in fiberglass and resin composites	350-700	Lighter and with thinner walls. Used mainly in mobility applications and to transport hydrogen in trailers
Type IV. Non-metallic coating wrapped up in polymer fibre and coating		

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2.8.2 Liquid Hydrogen:

By reducing the temperature to -253°C hydrogen converts to liquid form see figure



Fig. (2.10) Liquid Hydrogen.

(2.10), which is more suitable for distribution of large quantities. Liquid hydrogen storage is also a mature technology (Rivard *et al.*, 2019).^[21]

Liquid hydrogen at 0.1 MPa (1 bar) contains about four times more energy per volume unit than compressed hydrogen at 250 bar and almost three times as much as for 350 bars (Berstad *et al.*, 2009)^[22]. However, the method to achieve this also consumes 25-35% of the original energy content (IDEALHY, 2013) and the extremely low temperature required is associated with technical challenges^[23]. A liquid hydrogen tank is designed to reduce heat transfer to a minimum. Since the tank is not designed to hold high pressure, hydrogen is allowed to escape to a relief valve, or "boil-off", which means that an unused reservoir eventually will deplete itself (Rivard *et al.*, 2019)^[21]. This means that liquid hydrogen is most applicable where high energy density is required and boil-off is less of a concern.

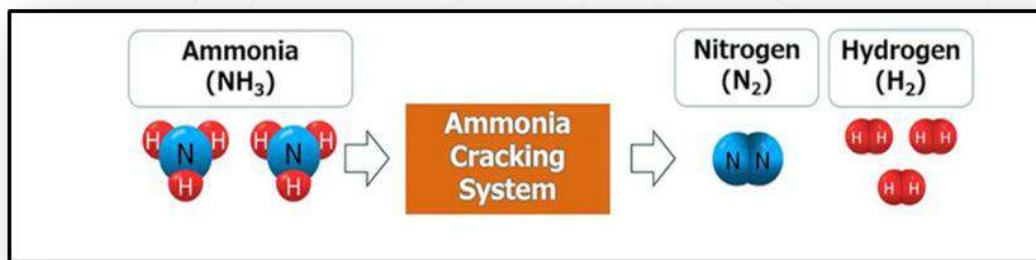
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2.8.3 Liquid Hydrogen Organic Carriers (LHOCs):

LOHCs are chemical compounds with high hydrogen absorption capacities, which represent another option for binding hydrogen chemically (Von Wild *et al.*, 2010) ^[23]. The advantage of these technologies is the ability to use existing infrastructure, such as tankers and tanker trucks (He *et al.*, 2015; Rivard *et al.*, 2019) ^[21]. Nierman *et al.* (2019) ^[24] found that methanol is the cheapest LOHC option for storage and transportation. For a storage time of 60 days under defined assumptions, this solution showed economic advantages compared to compressed hydrogen. Even though LOHC options are still at early stage, they show potential for long-term storage/long distance transport applications. ^[24]

2.8.4 Ammonia:



Fig, (2.11). Ammonia's atomic make-up means it can carry hydrogen and then be “cracked” to release it.

The possibility of using ammonia as a hydrogen carrier is increasingly discussed. Compared to other hydrogen storage materials, ammonia has the advantages of high hydrogen density, a well-developed technology for synthesis and distribution and easy catalytic decomposition (Klerke *et al.*, 2008). According to Rivard *et al.* (2019), the energy density is only marginally better than for liquid hydrogen, but the vapor pressure is much lower and this simplifies the tank design. On the other hand, the utilization of ammonia, as well as methane, is more difficult than pure hydrogen. Solid oxide fuel cells (SOFC) are the most likely route, but as noted above this technology is only emerging ^[23].

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The drawbacks are mainly the toxicity of liquid ammonia and tracing levels of ammonia in the hydrogen after decomposition (ibid).



Fig. (2.12) Using ammonia to transport hydrogen allows much greater volumes to be carried.

2.8.5 Storage in materials:

The crucial structural factor that affects the effectiveness of hydrogen storage in multilayered materials is the interlayer spacing as in Figure (2.13).

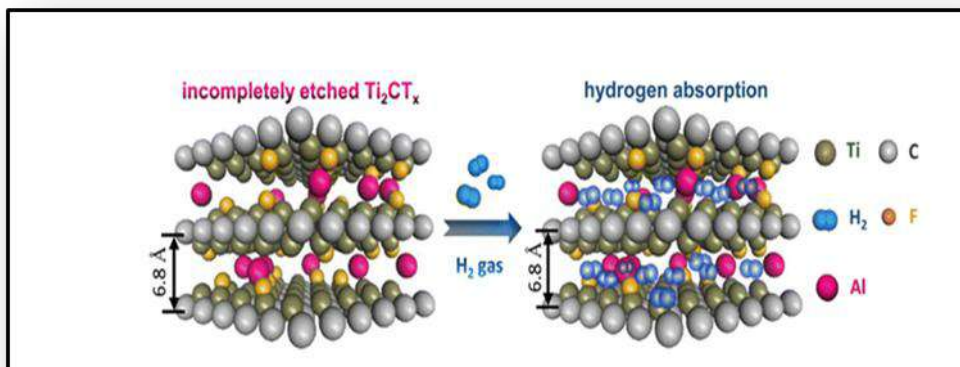


Fig. (2.13) Schematic illustration of hydrogen storage in the interlayer space of Ti_2CT_x

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The strength of hydrogen adsorption is influenced by the elemental compositions of the layer as well as by the functional groups on the layer. We believe that in addition to graphene and Mxene, many other multilayer materials, including montmorillonite, MoS₂, BN, and others, should be capable of storing hydrogen with a nanopump, but further research is required to determine the proper interlayer distances and surface functional groups^[25]

Some hydrogen carriers include methane, methanol, ammonia, methyl cyclohexane, sodium borohydride. A chemical reaction is needed to convert these products and release gaseous hydrogen. There are also metal powders that can absorb and release hydrogen (metal hydrides). They can store significant amounts of hydrogen at atmospheric pressure and room temperature, due to forces acting inside the metal crystal lattice. Metal hydrides are the most compact way to store hydrogen. They are more dense than liquid hydrogen.

Hydrogen can be stored in a gaseous form in both tanks or salt caverns, as a cooled liquid, in a metalloid framework, or as a hydrogen-rich substance like anhydrous ammonia. (Evans, Wolf, 2011; Rowsell & Yaghi, 2015 ;Schlapbach & Züttel, 2001).^[26] This host of storage options allows for a tailoring to specific applications. Concurrently, pipelines used for transmission and distribution, if packed with H₂, would serve effectively as additional product storage. This capacity for wide-scale long-term storage makes hydrogen a promising energy carrier to service consumers previously utilizing liquid or gaseous hydrocarbon-based fuels.

2.8.6 geological storage:

Compressed gaseous hydrogen may also be stored in underground natural caverns, which presently are used for storage of compressed natural gas. Blue Move (2017).^[27] Figure (2.14).

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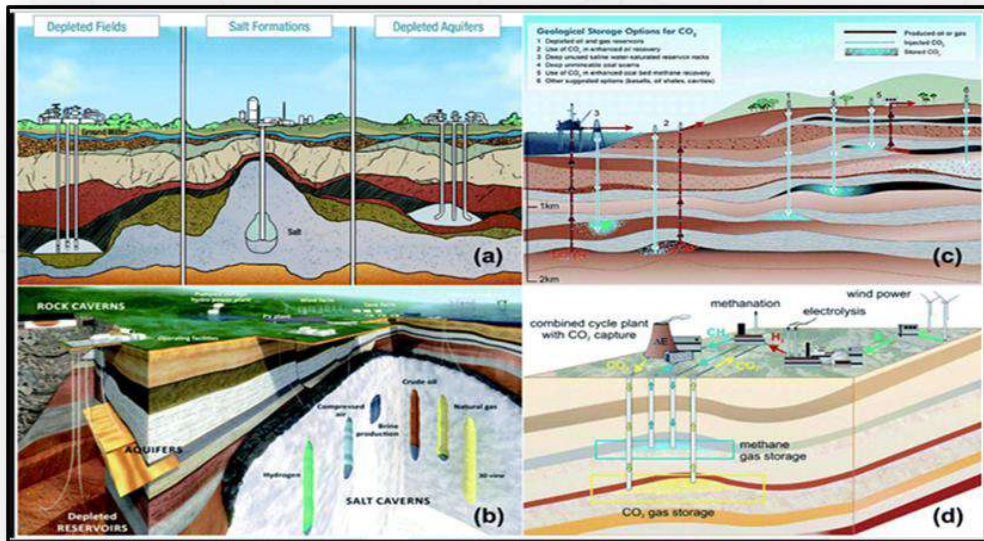


Fig (2.14). Illustrations of viable geologic formations and schematic representations for (a) general underground storage of various substances (including H_2) in depleted hydrocarbon deposits, salt formations and aquifers;⁶⁵ (b) natural gas, liquid hydrocarbons, compressed air, hydrogen, and brine storage in salt caverns (showing cross-section through a salt dome);⁶⁶ (c) carbon geo-storage (CGS);^{58,67} (d) integrated CO_2 and CH_4 storage.⁶⁸

The other technology in use at present (for natural gas storage) is deposit in cavities created in salt domes, i.e. intrusions of geological salt layers towards the atmospheric surface. Such cavities can be formed by the inexpensive method of flushing with water, following which it may be necessary to seal the inside walls, depending on the integrity of the salt structure ^[27].

For leakage through the salt itself, modeling similar to the one for aquifers can be performed ^[28]. If the integrity of the salt formation is low, canisters lowered into the flushed holes may be used, in order to completely eliminate the leakage problem, albeit at a cost. For most installations, the salt itself constitutes a sufficient barrier to avoid leakage.

Advanced Clean Energy Storage, the world's largest renewable energy storage project, was recently announced and will be located in Utah, United States. Advanced Clean Energy Storage will show off technologies that will be critical in a future decarbonized power grid. An Excess renewable energy hydrogen will be stored in a series of underground salt caverns.

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Part of the project. Enough renewable hydrogen will be stored in a single cavern to provide 150,000MWh of clean energy storage. Mitsubishi Hitachi Power Systems will supply the technology for converting excess renewable electricity into 'green' hydrogen. Storage of gas in salt caverns is a well-established technology that facilitates knowledge transfer. ("Micro-H₂," 2011) ^[29].

2.9 Hydrogen fuel cell:

A fuel cell is an electrochemical device that generates electrical energy from fuel via an electrochemical reaction. The process is reverse of water electrolysis in which electric current breaks down water into hydrogen and oxygen ions. In fuel cells, hydrogen (fuel) and oxidizer (oxygen or air) react chemically to generate electricity, heat, and water.



Fuel cells work like batteries: hydrogen is fed to the anode; oxygen is fed to the cathode; they are separated by a catalyst and an electrolyte membrane that only allows positively charged protons through to the cathode. The catalyst splits off the hydrogen's negatively charged electrons, allowing the positively charged protons to pass through the electrolyte to the cathode. The electrons, meanwhile, travel via an external circuit—creating electricity that can be put to work—to meet the protons at the cathode, where they react with the oxygen to form water. Because they can function independently from the grid, fuel cells can be used in the military field or in disaster zones and work as independent generators of electricity or heat. When fixed in place they can be connected to the grid to generate consistent reliable power^[30]

Proton Exchange Membrane (PEM) fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet. Efficiency is about 40 to 50 percent, and operating temperature is about 80 degrees C (about 175 degrees F). Cell outputs generally range from 50 to 250 kW. The solid, flexible electrolyte will not leak or crack, and these cells operate at a low enough temperature to make them suitable for homes and cars. But their fuels must be purified, and a platinum catalyst is used on both sides of the membrane, raising costs^[31]. The most important components of the Cell are shows in the figure (2.15)

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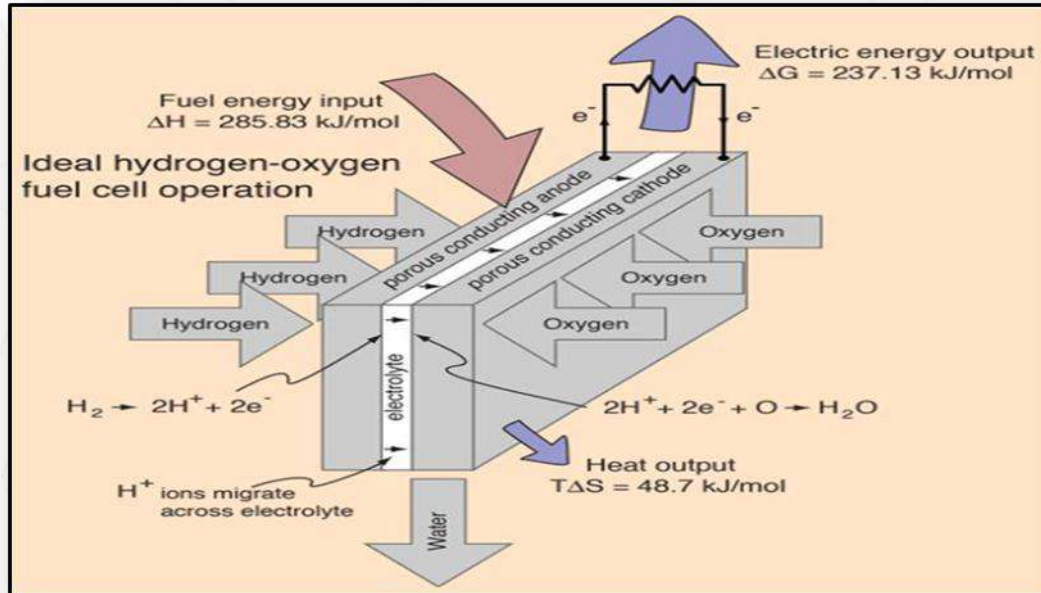


Fig.(2.15) The main component of the PEMfuel Cell.

The Figure(2.16) below illustrates the electrochemical process in a typical fuel cell.

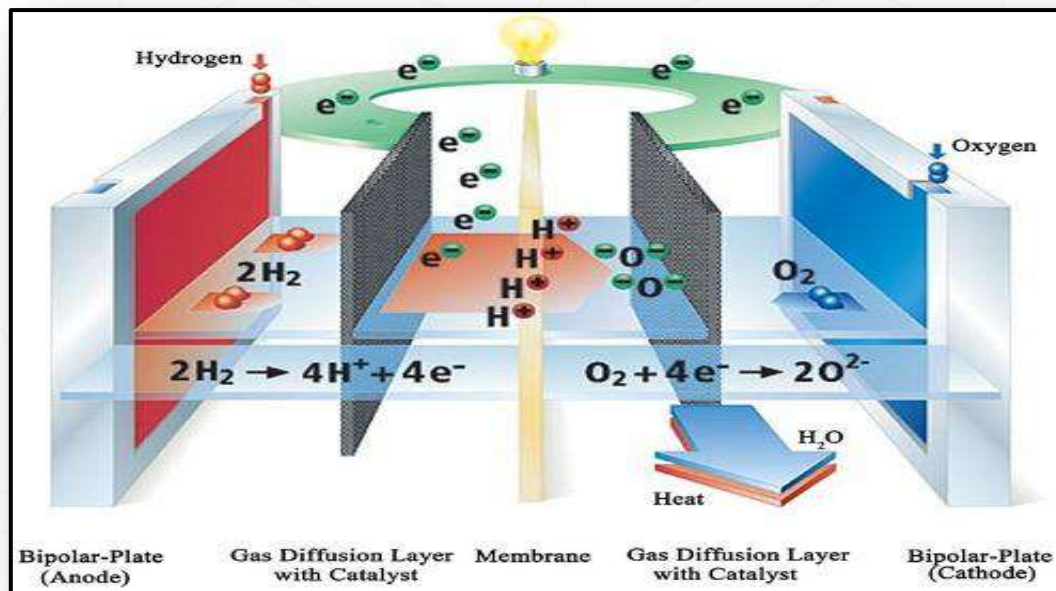
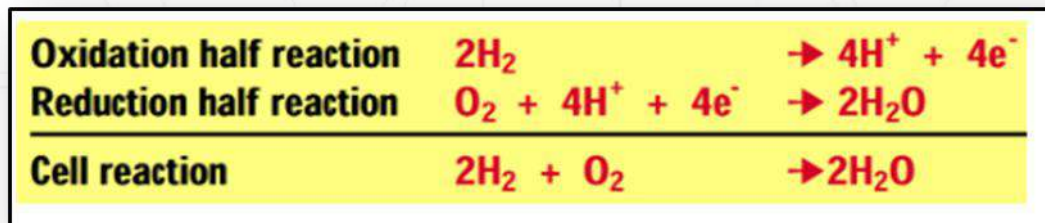


Figure. (2,16) illustrates the electrochemical process in a typical fuel cell.

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Fuel cell power systems convert the chemical energy of a fuel and an oxidant directly into electrical energy and heat using electrochemical processes not combustion.



Perhaps the simplest system, a Proton Exchange Membrane Fuel Cell (PEMFC), combines hydrogen fuel with oxygen from the air to produce electricity, water, and heat. This process is essentially the reverse of electrolysis of water. The electricity results from free electrons liberated from hydrogen at the anode flowing through an external electrical circuit before recombining with hydrogen ions^[32]

In many ways, the fuel cell is analogous to a battery. The key difference between batteries and fuel cells is that while batteries store energy, fuel cells produce electricity continuously if fuels are supplied. The first commercial usage of fuel cells was in the 1960s when NASA utilized them to power satellites and space shuttles.

2.9.1 Comparison of Fuel Cells with Batteries:

Fuel cells and batteries are both galvanic cells and therefore have many similarities. Both fuel cells and batteries consist of an anode and a cathode in contact with an electrolyte. Both devices generate electrical energy by converting chemical energy from a high energy state to a lower energy state using an electrochemical reaction. These reactions occur at the anode and cathode with electron transfer forced through an external load in order to complete the reaction. Individual cells of both batteries and fuel cells generate only small DC voltages, which are then combined in series to achieve substantial voltage and power capacities. Fuel cells differ from batteries in the nature of their anode and cathode. In a battery, the anode and cathode are metals; zinc or lithium is typically used for the anode and metallic oxides for the cathode. In a fuel cell, the anode and cathode are composed of gases often in contact with a platinum catalyst to promote the power generating reaction.

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Hydrogen or a hydrogen-rich gas mixture is typically used as the anode and oxygen or air as the cathode. Fuel cells also differ from batteries in the fundamental method in which the chemical reactants are stored. In a battery, the anode and cathode form an integral part of the battery structure and are consumed during use. Thus, battery can only operate until these materials are fully consumed. Key Points & Notes assumed after which it must either be replaced or recharged, depending on the nature of the materials. In a fuel cell, the chemical reactants are supplied from an external source so that its materials of construction are never consumed and do not need to be recharged. A fuel cell continues to operate as long as reactants are supplied and the reaction products are removed^[33]

2.9.2 Applications of full cell:

Proton exchange membrane fuel cells were first used by NASA in the 1960's as part of the Gemini space program, and were used on seven missions. Those fuel cells used pure oxygen and hydrogen as the reactant gases and were small scale, expensive and not commercially viable. NASA's interest pushed further development, as did the energy crisis in 1973. Since then, fuel cell research has continued unabated and fuel cells have been used successfully in a wide variety of applications. Applications Fuel cells are inherently modular and therefore lend themselves to a wide range of applications, from large stationary power plants, automobiles to small portable power packs Figure (2.17).



Fig. (2.17). Current fuel cell truck concepts: Kenworth/Toyota fuel cell electric truck.

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2.9.3 PEM Fuel Cell History:

PEM technology was invented at General Electric in the early 1960s, through the work of Thomas Grubb and Leonard Niedrach. GE announced an initial success in mid-1960 when the company developed a small fuel cell for a program with the U.S. Navy's Bureau of



Fig. (2.18) GE's Thomas Grubb (right) and Leonard Niedrach run a fan with a diesel-powered PEM fuel cell in [April 1963]

Ships (Electronics Division) and the U.S. Army Signal Corps. The unit was fueled by hydrogen generated by mixing water and lithium hydride. This fuel mixture was contained in disposable canisters that could be easily supplied to personnel in the field. The cell was compact and portable, but its platinum catalysts were expensive.

2.9.4 Regenerative Fuel cell System:

Energy storage and transportation technologies play an important role in space exploration missions. Regenerative fuel cells are among the most promising sustainable energy power sources. Compared to secondary batteries, regenerative fuel cells possess unique advantages, including high power density, high specific energy density, light-weight, low-cost, high-efficiency, long-life, and zero environmental impact. More importantly,

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a regenerative fuel cell is an electrochemical device that can collect and store solar energy during the daytime and release it gradually whenever is needed, see Figure (2.19).

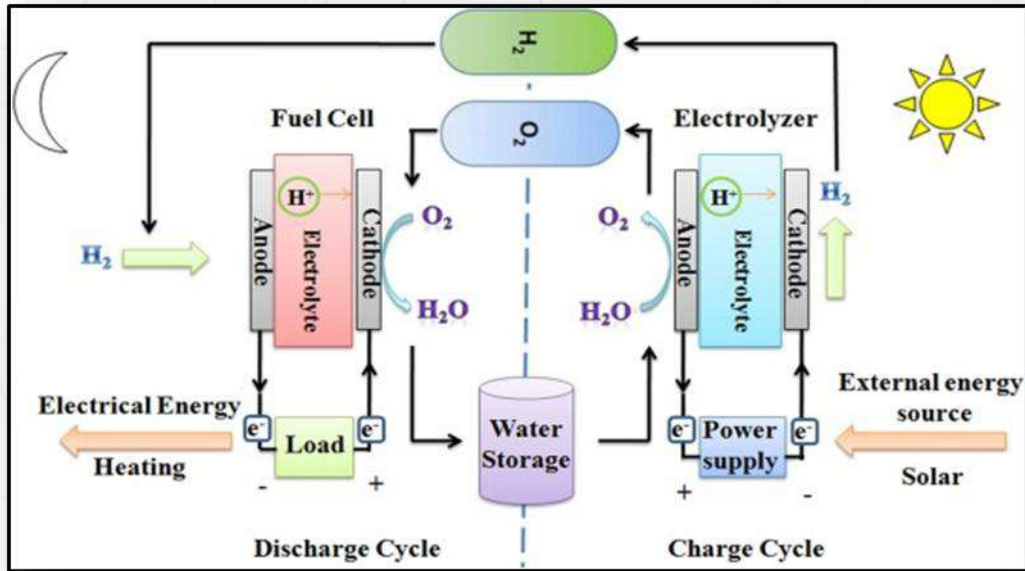


Fig.(2.19) Regenerative fuel cells

2.9.5 Fuel cell efficiency:

Fuel cells are driven by electrochemistry, not combustion, and therefore are more efficient than conventional power plants (direct energy harvesting). Figure (2.20) shows that.

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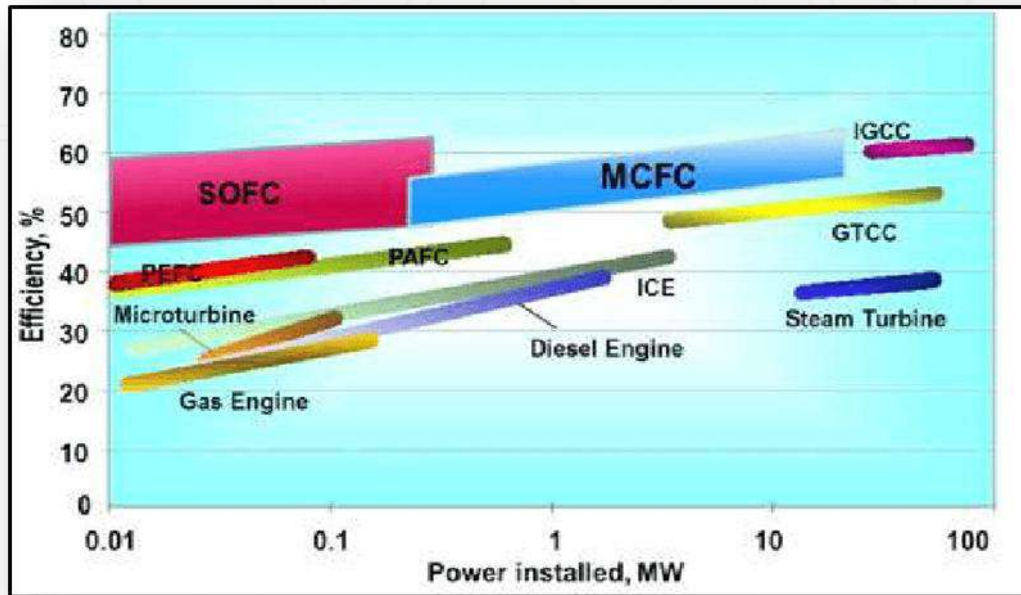


Fig (2.20). Electric efficiency of the systems according to their production technology ^[21] (DMFC-direct methanol fuel cell-MCFC-molten carbonate fuel cell-fuel cell with molten carbonate, SOFC-solid oxide fuel cell-cell solid oxide fuel).

2.9.6 Advantages of Fuel Cells:

Fuel cell systems are usually compared to internal combustion engines and batteries and offer unique advantages and disadvantages with respect to them. Fuel cell systems offer the following advantages:

Fuel cell systems operate without pollution when run on pure hydrogen, the only by-products being pure water and heat. When run on hydrogen-rich reformat gas mixtures, some harmful emissions result although they are less than those emitted by an internal combustion engine using conventional fossil fuels. To be fair, internal combustion engines that combust lean mixtures of hydrogen and air also result in extremely low pollution levels that derive mainly from the incidental burning of lubricating oil. Fuel cell systems operate at higher thermodynamic efficiency than heat engines. Heat engines,

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such as internal combustion engines and turbines, convert chemical energy into heat by way of combustion and use that heat to do useful work.

2.9.7 Fuel cells have three main applications:

- Transportation.
- Portable uses.
- Stationary power installations.

Figure (2.21) below shows some stationary power fuel cells.

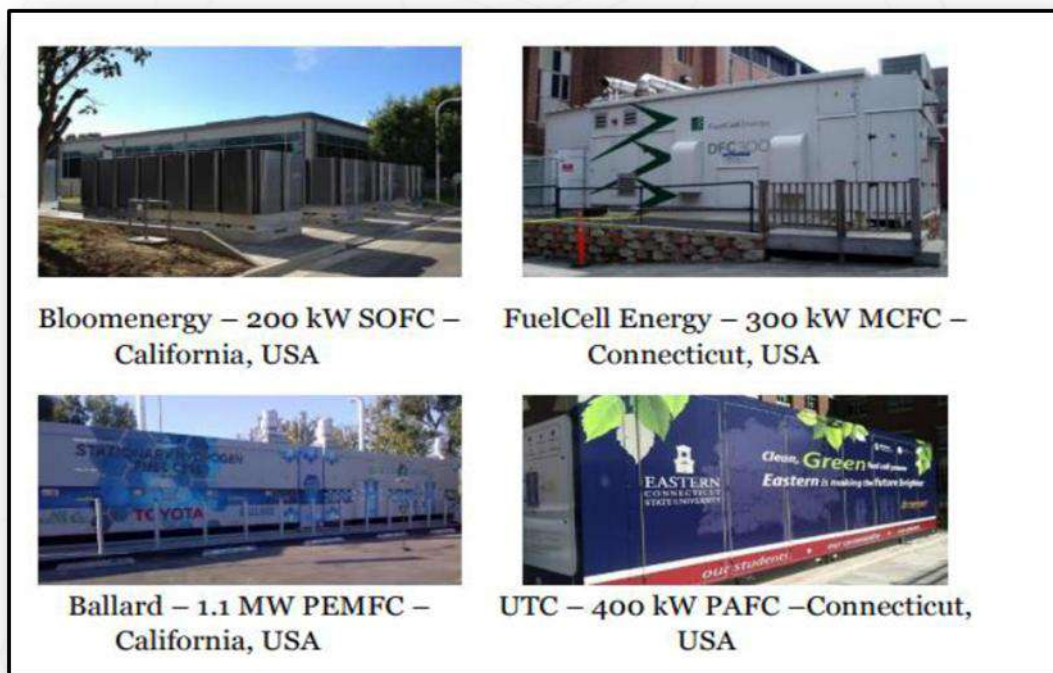


Fig. (2.21) stationary power fuel cells.

2.11 Challenges of Hydrogen Storage & Transportation:

2.11.1 Storage Problems:

- **Low Energy Density:** With a low volumetric energy density, the storage becomes a little challenging within a limited space. Therefore, traditional storage methods would often require pressurized large and heavy containers that would impact the feasibility of using hydrogen in certain applications.

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- **Material Compatibility:** Being a small and reactive molecule, Hydrogen can permeate through many materials, leading to issues like embrittlement and reduced structural integrity in storage materials.
- **Compression and Liquefaction:** One would require energy-intensive high compression or liquefaction processes to store hydrogen in a gaseous state at high pressure or as a liquid at low temperatures. They could result in significant energy losses thus making the overall hydrogen storage system less efficient.
- **Temperature Sensitivity:** Hydrogen's physical properties make it sensitive to temperature changes. Therefore, it is vital to maintain the appropriate storage conditions while ensuring the safe handling of hydrogen.
- **Cost of Storage Technologies:** It is by far the most significant roadblock in Hydrogen's widespread adoption as an energy carrier. Also, the development and implementation of advanced storage technologies come with higher initial costs.

2.12 Hydrogen Transport:

To be transportable hydrogen needs to be compressed, liquefied or chemically combined. Safe and cost-efficient transport and distribution of hydrogen is critical for its large-scale deployment. Hydrogen's low energy density, high diffusivity, and high flammability.

2.12.1 Means of transportation:

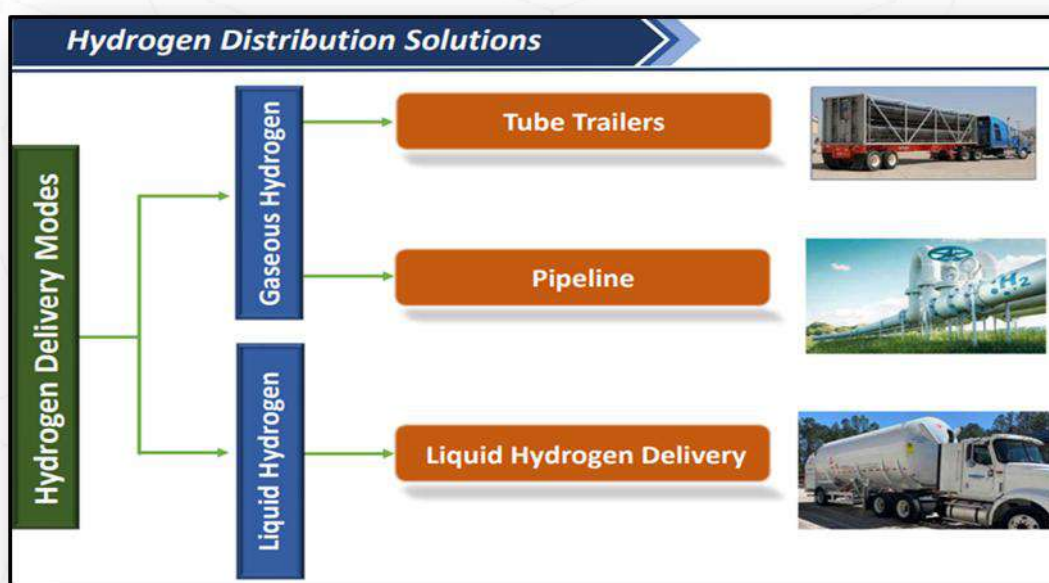


Fig. (2.22) Hydrogen Distribution Solution.

Road and runway: A common method of hydrogen transport is in pressure-proof filled cylinders on a truck Figure (2.23). These vessels can be either of industrial standard size (up to 150 litres volume), or larger tubes.

Marine Transportation: The first hydrogen cargo ship – Suiso Frontier – was commissioned in 2019 to transport hydrogen from Australia to Japan in one 1250m³ (= 88 tones H₂) vacuum insulated tank at -253C/1atm.

Pipelines: Hydrogen can be transported by pipelines as pure compressed hydrogen as ammonia. Transporting pure hydrogen makes economic sense for a distance of less than 3,500 km; for longer distances ammonia route is a more economically viable option.

There are some difficulties with large-scale generation, storage, transportation, and consumption of hydrogen as an energy carrier. The round-trip efficiency for energy storage (hydrogen-electricity) of most mainstream conversion technologies is low in comparison to other energy storage technologies. Additional problems exist with the transmission and distribution of hydrogen. Chemical properties of the molecule make it extremely prone to both leakage and embrittlement of metallic pipeline, although specialty polymer pipes are currently in production that are resistant to leakage and embrittlement. Low energy-to-volume ratio in its gaseous state makes it expensive to transport by truck and unrealistic by ship. Finally, a lack of maturity in the hydrogen sector results in a scant force of people qualified to work with H₂ relevant technologies.

2.12.2 Hydrogen Transportation Challenges:

- **Infrastructure Development:** Establishing a comprehensive hydrogen transportation infrastructure is a significant challenge as it includes pipelines, storage facilities, and distribution networks.
- **Safety Concerns:** Because of the wide flammability range, and its combustion characteristics, it is vital to address safety concerns related to hydrogen transportation which would require public acceptance and regulatory approval.
- **Material Compatibility in Pipelines:** Hydrogen can embrittle certain metals, potentially leading to pipeline failures. Thus, maintaining safety and structural integrity would remain an ongoing challenge while developing pipelines and materials that are compatible with hydrogen.

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- **Hydrogen Purity Requirements:** Many applications of Hydrogen in the practical world, such as fuel cells would require high-purity hydrogen. And, thus ensuring the purity during transportation would require additional purification steps, adding complexity and cost to the overall system.
- **Mode of Transportation:** Determining the most efficient mode of hydrogen transportation has been a topic of several ongoing debates. While pipelines have proven to be the most suitable option for large-scale transportation, today alternative methods such as trucks, ships, or even ammonia carriers are being tried out for long-distance transport.
- **Economic Viability:** The cost-effectiveness of hydrogen transportation methods would ascertain the overall success of hydrogen as an energy carrier. And at this stage balancing the infrastructure development costs with safety measures, and transportation technologies is proving to be a complex task.

2.13 Hydrogen end-use applications:

2.13.1 Application of Hydrogen across sectors:

Current use of hydrogen is dominated by industrial applications. Particularly the chemical industry accounts for around 93% of worldwide consumption, with most of it (53% of total) used for the production of ammonia (Velazquez Abad & Dodds, 2017)^[34]. Figure (2.24) Potential changes in this sector revolve around the introduction of CCS technologies in the processes or replacement of the used hydrogen which as much low-carbon or green hydrogen as possible. Also in the industrial sector, hydrogen can be used to substitute fossil fuels in steel production, oil refining and as a source of high temperature heat (IEA, 2019).^[35] as Figure (2.24) Overview of hydrogen usage and production in the model.

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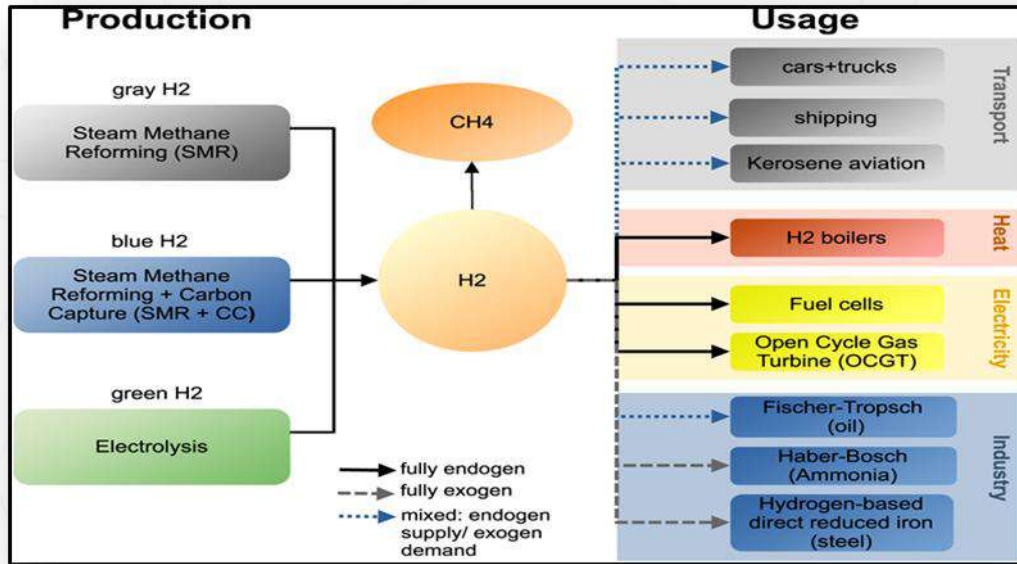


Fig (2.23). Application of Hydrogen across sectors.

However, hydrogen has the potential to be used in other sectors as well, especially in applications where direct electrification proves challenging. In the transport sector hydrogen fuel cells can be used to power vehicles which are either too large or require long driving ranges, such as buses or trucks. The same approach can also be applied to trains in areas difficult to electrify. In the shipping and aviation sectors, hydrogen can be used as feedstock for producing low carbon high energy fuels. Finally, hydrogen shows promise to be used in the heat and power sector, mainly by being blended into the existing gas network for heat delivery in buildings and as an alternative to balance power generation in an increasingly variable electric grid (IEA, 2019).^[35]

Use in transport:

According to the Hydrogen Roadmap Europe, the EU alone needs to eliminate about 72% of CO₂, equal to roughly 825 Mt, from the transportation fleet by 2050 (FCH-JU, 2019).^[36] On a tank-to-wheel basis, FCEVs and battery-electric vehicles (BEVs) are the only fully CO₂ emission free alternatives. Hydrogen provides sufficient power for long ranges and high payloads due to its superior energy density Figure (2.25), and hydrogen infrastructure, while initially a barrier, has significant benefits at scale compared to fast charging.

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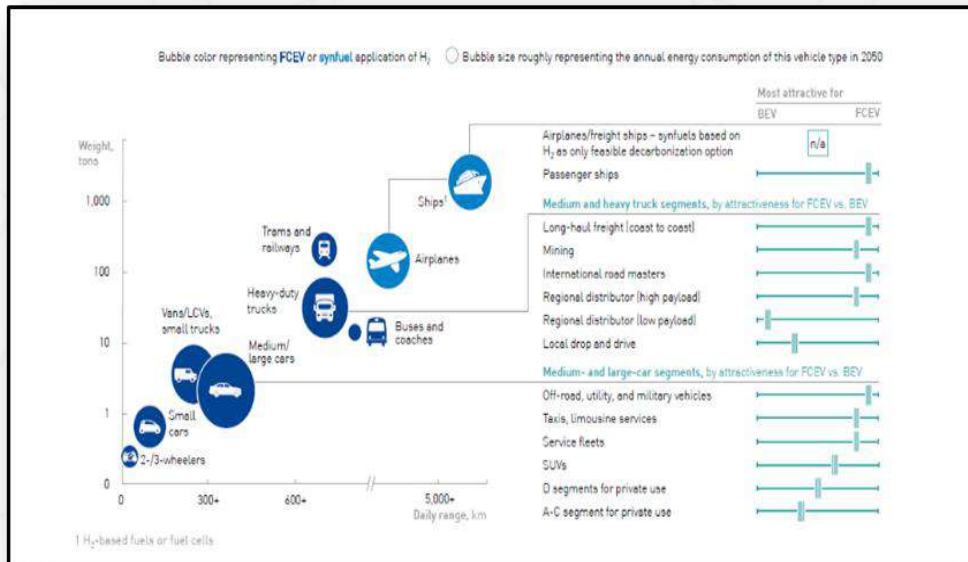


Fig. (2.24) Hydrogen Bus.

Lastly, hydrogen is considered as a promising option for trains and ships, as are hydrogen-based synthetic fuels for aviation. The overall prospects for hydrogen in transport towards 2050 are positive, as illustrated below (Figure 2.28).^[36]

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Fig, (2.25). comparison of rang, payload, and preferred technology towards 2050 (FCH JU 2019:27).

The projections for hydrogen deployment in the transport sector do, however, vary significantly. Most forecasts expect battery electric vehicles to take the largest market share of the transport sector. Battery capacity, weight, and price will be important factors for the future share of battery electric vehicles. Battery performance is increasing, but as demand increases, prices of input factors such as depletable resources will increase. Valma et al. (2018) points out that even with low-cobalt cathode materials, the demand for Lithium and Cobalt until 2050 will outpace the world's known reserves.

Globally, (DNV GL 2018) ^[37] expects a higher proportion of biofuels than hydrogen in the fuel mix in the transport sector, and thus only a modest hydrogen share in the transport sector in 2050. For heavy vehicles they expect a hydrogen fuel share of less than 5%, and for light vehicles they expect a fuel cell electric vehicle share of 5 to 13% in 2050. They do, however, foresee that the share of hydrogen will increase onwards. Shell Sky (2018). ^[38] does not include biomass in the transport sector and expects this sector to continuously depend on fossil fuels, with a less than 3% hydrogen share in transport in 2050.

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Fig.(2.26). Illustrations of innovative hydrogen fueled highspeed passenger vessel concept.

Left photo: Brodrene Aa. Right photo: Selfa Aretic

Hydrogen is used for exploring outer space:



Fig. (2.27) Energy Storage Options for Space Applications.

The National Aeronautics and Space Administration (NASA) began using liquid hydrogen in the 1950s as a rocket fuel Fig. (2.28), and NASA was one of the first to use hydrogen fuel cells to power the electrical systems on spacecraft.

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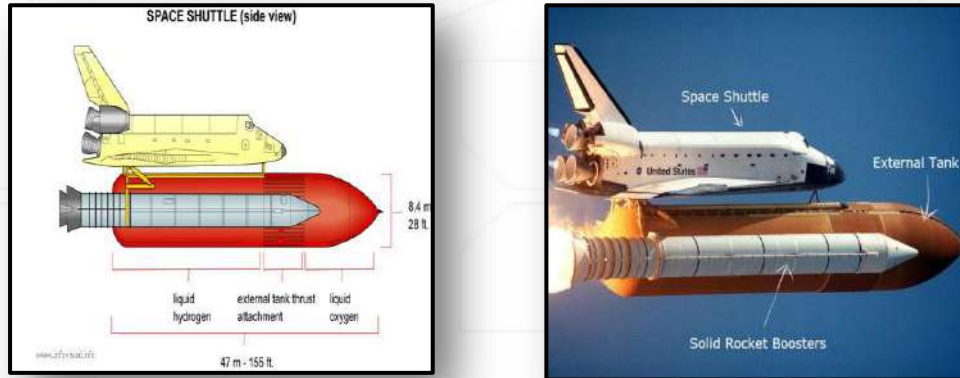


Fig. (2.28) space shuttle (side view): reusable space vehicle used for travel between a space station and earth.

Liquids oxygen: tank containing liquid oxygen to feed the engines.

External tank thrust attachment: separation between two tanks.

Liquid hydrogen: tank containing liquid hydrogen for fueling the engines.

As you can see from the diagram, the space shuttle main engines burned hydrogen for fuel. They used liquid hydrogen, burning with liquid oxygen, mostly because that let more fuel and oxidizer combine more rapidly, producing higher thrust. Gaseous hydrogen and oxygen could of course be used, but since these gases take up vastly more space, such an engine would produce.

Hydrogen feed stocks:

Green hydrogen is being used to replace existing hydrogen feed stocks. While burning hydrogen only emits water, the process of producing hydrogen can be very carbon-intensive. Hydrogen produced via green hydrogen methods, however, is produced using renewable energy instead of fossil fuels.

Energy storage:

Green hydrogen, produced using renewable energy, could decarbonise some of the most energy.

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A major application of traditional hydrogen energy is to produce fuel cells. While this significant challenge must be overcome before green hydrogen can be used in energy storage, recent studies have shown that green hydrogen for energy storage applications is cost-effective when Energy storage is required for more than 13 hours.

Alternative fuel production:

The fourth major application of green hydrogen is in the production of alternative fuels. Currently, scaling-up green hydrogen production for a range of applications faces a challenge is to convert hydrogen into a less volatile and less flammable compound such as ammonia or methane. However, as energy is lost in this conversion, this approach is only appropriate when the resultant product has a relatively high value.

Fuel cell vehicles:

Green hydrogen is being used to power fuel-cell vehicles. This application of green hydrogen is one of the most often cited uses of the renewable energy source, however, green hydrogen fuel-cell vehicles have yet to gain significant traction in the automotive market. It is 100% sustainable and does not emit any polluting gas either during the process of Electrolysis or while being used.

Use for heating:

Hydrogen is also associated with a large potential of decarbonizing the heating sector in countries reliant on natural gas. DNV GL (2018).^[37] sees a great potential in areas with an existing natural gas infrastructure. Both the Energy Transition Commission (2018) and The Hydrogen Outlook Europe (2019) expect hydrogen to cover 10% of the heat demand in 2050.

A review of the existing research literature suggests that it is feasible, technically and safety-wise, to introduce a hydrogen share of up to 20% into the existing gas infrastructure without significant interventions (Hodges *et al.*, 2015).^[39] The hydrogen - natural gas mix - has a slightly lower efficiency, both in terms of heating value and density (Dashtebayaz *et al.*, 2019).

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^[40] However, climate gas emissions will be significantly reduced, and there are huge savings to be made by utilizing the existing infrastructure for natural gas transmission and storage (Nastasi and Basso, 2016). ^[41] Green hydrogen is mixed with natural gas as a ‘quick fix’ to reduce heating-related emissions. However, this is only feasible where natural gas prices are relatively high.

Power for remote areas:

In remote areas where electricity transmission is expensive, the fossil solution will also be expensive due to high transport costs. In remote islands, the cost of developing and maintaining the power supply from shore through sea cables may be ten times higher than for urban areas. In such areas, hydrogen stands out as a profitable alternative

Use in industry:

IEA's Technology roadmap for Hydrogen and Fuel Cells (2015) finds the greatest potential for hydrogen in industry. The industry sector accounts for one fifth of the world's direct global greenhouse gas emissions and has so far had very little progress on decarbonisation (Stafell, 2019) ^[42]. Hydrogen is already widely used as feedstock and produced as a by-product in chemical manufacturing processes. Hydrogen may also replace natural gas as a fuel; burners and furnaces may need replacement, but industry application will not require high purity. Stafell (2019),^[42] notes that hydrogen could be introduced into several high-temperature industries including steelmaking and cement. However, commercialisation is not expected before 2030 due to low maturity, uncertain costs, the likelihood of needing fundamentally redesigned processes, and the slow turnover of existing systems. This is in line with the Shell Sky scenario (2018) ^[43], which anticipates a hydrogen share in industry in 2050 of 3%.

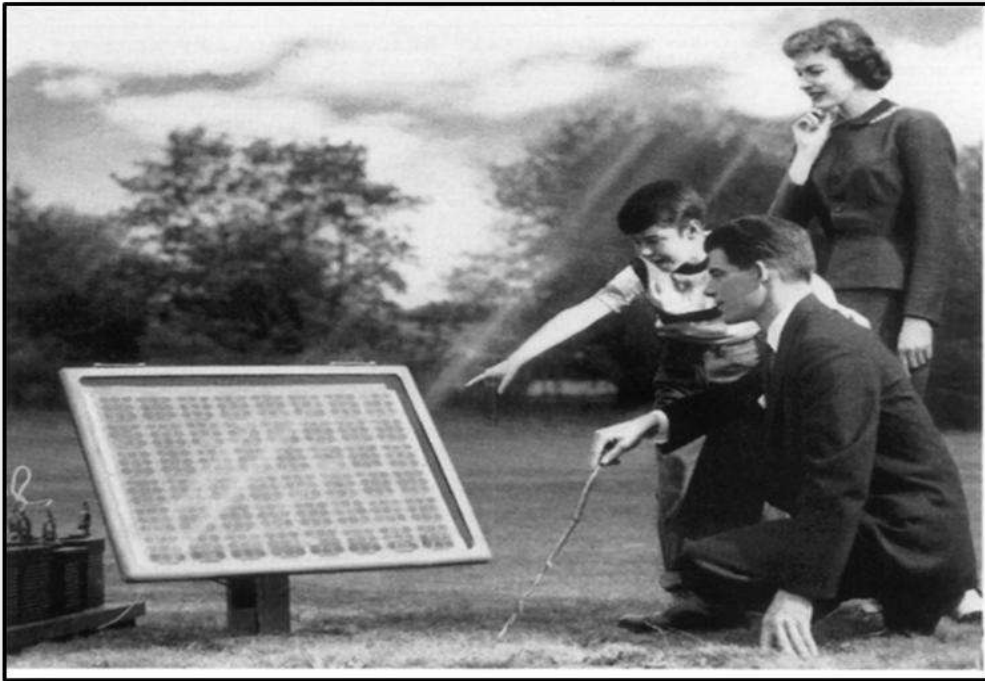
Several studies highlight the potential for emission reductions associated with introduction of renewable hydrogen into gasoline production. A recent study for Ontario, Canada, finds that renewable hydrogen may decrease 4.6% of the natural gas consumption of the gasoline cycle, and thereby minimize carbon intensity by 0.15 kg CO₂e per 100 km (0.5g CO₂e per MJ) of the fuel (Alsubaie *et al.*, 2019) ^[43]. A comprehensive review of realized power-to-gas projects in Europe (Wulf *et al.*, 2018) ^[44] also indicates that the application in industry, and for reducing the carbon footprint of refineries, will be important in future.

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CHPATER 3

3.1 Introduction:



Fig(3.1).: Photography used for the TIME magazine on May 1954 to announce the release of the first commercial solar panel.[45]

Something New Under the Sun. It's the Bell Solar Battery, made of thin discs of specially treated silicon, an ingredient of common sand. It converts the sun's rays directly into usable amounts of electricity. Simple and trouble-free. (The storage batteries beside the solar battery store up its electricity for night use.)

For the first time in the history of humanity, in 1954, the Bell Telephone Laboratories announced to the world the successful discovery of a device that was able to convert the sun's rays into useful electricity. This was the first commercial solar cell with about an efficiency of 6%. "...This device has great possibilities for telephone services and all humanity...", quoted the TIME magazine in an article of that year ^[45].

Sixty-four years later, it turns out that not only the predictions were correct; they even underestimated the utility of solar panels. Photovoltaic (PV) technology has evolved at an amazing speed in the last decade. Both lower prices and higher conversion efficiencies have made solar electricity to become more attractive to the industry and consumers. Steadily, PV technology is becoming one of the most important energy technologies of our time.

The current record lab cell efficiency, for mono-crystalline silicon solar cell, is 26. 7%. The price of PV systems reached € 1,270 per kilowatt peak (kWp) in the German market at the end of 2016 ^[27]. Furthermore, Trina Solar, the world's largest solar module manufacturer, produced PV modules with a total capacity of 5.74 GW in 2015 ^[46]. In summary, efficiency improvements, growth in manufacturing, and declining prices are three factors that have allowed the PV technology to break records in installed capacity.

3.2 Falling Prices of Photovoltaic Cells:

During the last 30 years, the price of solar panels has shown a dramatic decline in price. The cost of solar panels has decreased by a factor of 250, going from \$76 in 1977 to \$0.30 per watt in 2015. (Figure 1.2) shows the experience curve of PV technology, also known as the learning curve. This curve reflects the reductions in costs as a result of technological improvements and economies of scale. In the history of energy technology, there is no record of such a dramatic decrease in price other than for photovoltaic cells. ^[47].

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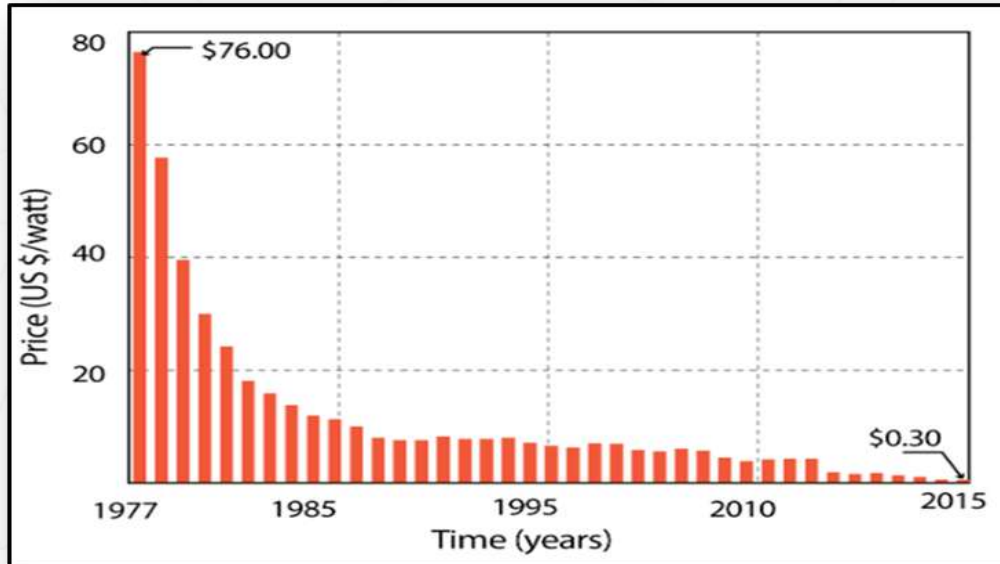


Fig.(3.2) Price history of silicon PV cells. (redrawing by author ^[35])

Learning rates in photovoltaic technology have experienced a very fast increase. PV modules learning rates have gone from 18% in 2010 to 22% in 2016. As a consequence, PV modules price dropped 80% since 2010 ^[52]. In the same period, the average cost of PV electricity from utility-scale fell from \$0.36 to \$0.11 per kilowatt-hour (kWh) ^[48]. Furthermore, the cheapest price ever to supply electricity, a \$0.0179/kWh for a 300 MW photovoltaic plant in Saudi Arabia was received by Electricite de France SA in 2017 ^[49]. Combining the excellent solar resources, the supportive governments and high-efficiency PV technology, even lower cost can be achieved. When looking at the PV systems cost, the cost of the balance of system (BOS) components is a relevant parameter. The PV module has the highest share in the cost price of a PV system at 55%, inverter at 11%, and 34% for the BOS ^[46]. Under an efficiency improvements, a BOS cost of €39 per kilowatt peak (kWp) is expected by 2050. An optimistic prediction for the same year, prognosticates a BOS cost of €29 per kWp.

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Even for pessimistic scenarios, assuming no major technological improvements, it is expected that the photo-voltaic industry will continue to experience important cost reductions. Depending on location and solar irradiance, a power cost of \$ 0.04 per kilowatt-hour ^[50] by 2025 and a \$0.02 per kilowatt-hour by 2050 is expected. Undoubtedly, solar energy is the cheapest forms of renewable energy. According to a report of Fraunhofer institute from 2015, even a conservative scenario will lead to significant PV growth in the future. ^[51].

3.3 Growth of Solar Power:

Declining prices of solar panels along with the necessity to reduce the world's CO₂ emissions create the perfect setting for turning the world's current energy system into one based on solar power generation. During 2016 ,solar energy was the fastest growing energy source worldwide ^[47]. For the first time, solar power exceeded the growth in power generation compared to all other power generation forms. Overall, renewable energy sources represent more than three-quarters of the newest electricity additions in 2016 ^[56]. Further- more, according to the prediction of the International Energy Agency (IEA), the capacity will significantly grow further in the next five years ^[53]

From 2015 to 2016, the PV installed capacity increased 33%, going from 227 GW to 320 GW of installed capacity. ^[54].

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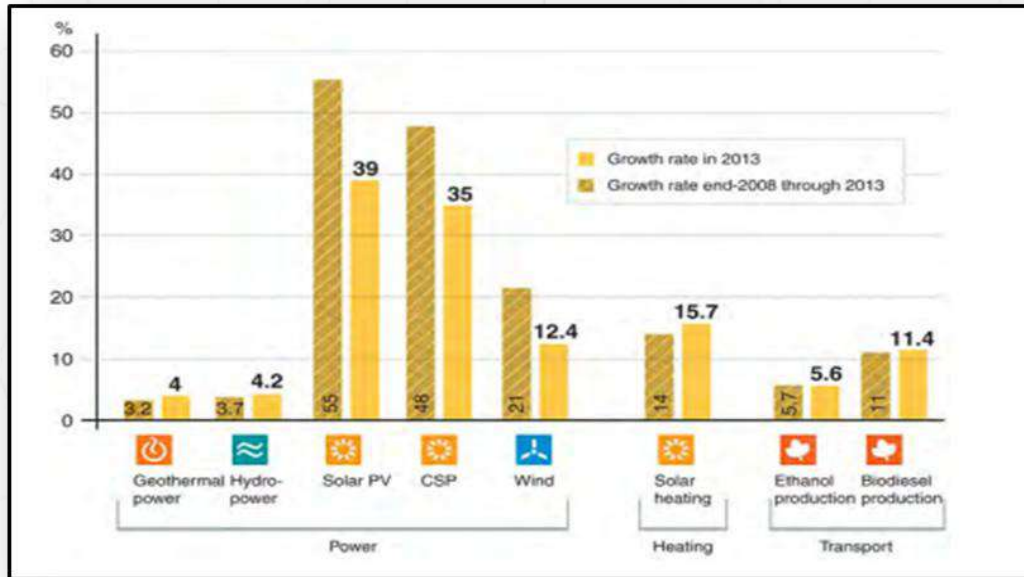


Fig. (3.3). Average annual growth rate renewable energy capacity and production, end 2008-2013.

This was a record in the history of the PV industry. This growth turned the PV technology into the fastest growing energy source in 2016, beating coal and gas with 75 GW of net additions. Leading the new PV installations was China with almost 50% of the installed capacity in 2016. Japan (42.8 GW), Germany (41.2 GW) and the United States (40.3 GW) follow China closely in the total cumulative installed capacity ^[55]. New to the PV industry are the developing countries as PV is a solution to the strong demand for electricity in rural areas where an electrical grid is lacking. However, due to their lack of financial sources, growth is limited in those countries (see Fig. (3.3)).

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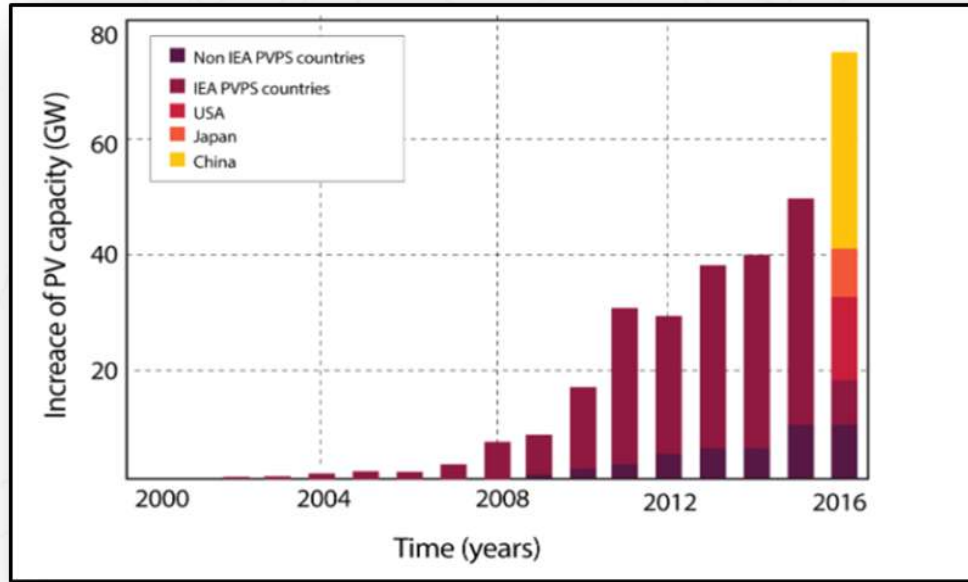


Fig. (3.4) Evolution of annual PV installations. (Redrawing by the author) [128]

Worldwide, the PV installed capacity accounts for approximately 1.8% of the electrical power demand of the planet ^[56]. Overall, coal is still the biggest electricity generation fuel with 9000 TWh. However, from 2015 to 2016 the electricity generation from renewable sources saw an increase in 6.8%, from 5627 TWh to 6012 TWh, mainly due to solar power ^[57]. In other words, the world's PV installed capacity keeps growing year after year which shows that renewable energy sources will become the dominant energy suppliers of the future. ^[54] Fraunhofer Research Institute. Photovoltaics report. (July), 2017.

3.4 Solar Photovoltaic Technology Basics:

The word “photovoltaic” can be divided into two parts: “photo” and “voltaic.” The term “photo” comes from the Greek word for light. A “volt” is a unit of measure for electric current. Thus “photovoltaic” literally means “electricity from light.” And that’s exactly what the word describes: capturing solar energy in the form of light and transforming it into electricity.

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What is photovoltaic (PV) technology and how does it work? PV materials and devices convert sunlight into electrical energy. A single PV device is known as a cell. An individual PV cell is usually small, typically producing about 1 or 2 watts of power. These cells are made of different semiconductor materials and

are often less than the thickness of four human hairs. In order to withstand the outdoors for many years, cells are sandwiched between protective materials in a combination of glass and/or plastics.

To boost the power output of PV cells, they are connected together in chains to form larger units known as modules or panels. Modules can be used individually, or several can be connected to form arrays. One or more arrays is then connected to the electrical grid as part of a complete PV system. Because of this modular structure, PV systems can be built to meet almost any electric power need, small or large.

PV modules and arrays are just one part of a PV system. Systems also include mounting structures that point panels toward the sun, along with the components that take the direct-current (DC) electricity produced by modules and convert it to the alternating-current (AC) electricity used to power all of the appliances in your home. show Fig. (3.5)

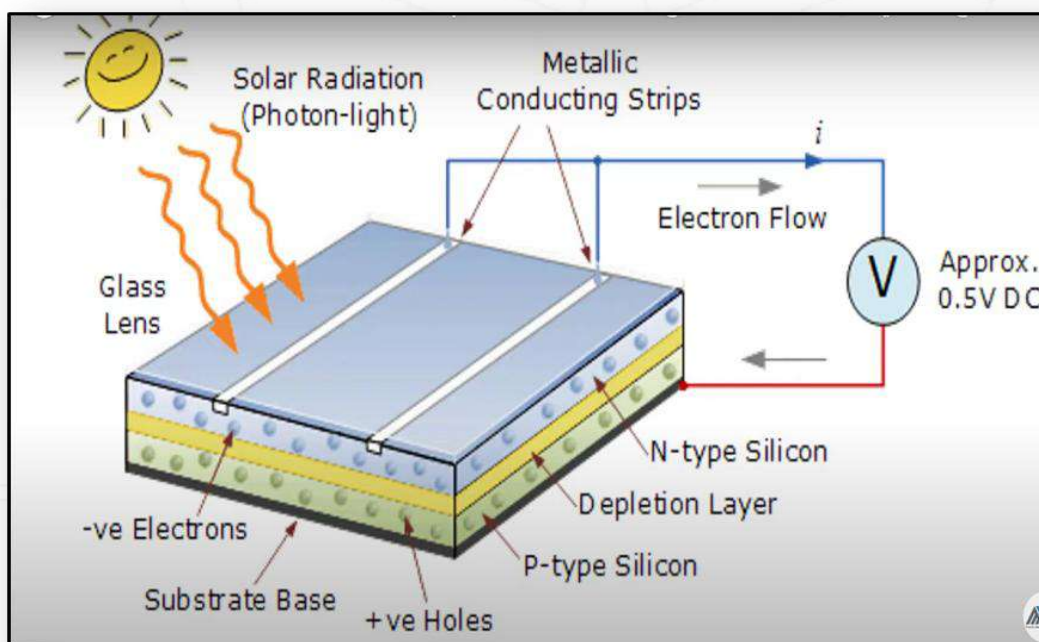


Fig. (3.5). Solar Cells Element.

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Note: that PV cell is just a converter, changing light energy into electricity. It is not a storage device, like a battery.

3.5 Benefits of PV Systems:

- a. **Environmentally friendly** - It has zero raw fuel costs, unlimited supply and no environmental issues such as transport, storage, or pollution. Solar power systems produce no air or water or greenhouse gases and produce no noise. Solar systems are generally far safer than other distributed energy systems, such as diesel generators and as such are the most suitable technology for urban on-site generation. PV is the only commercially available renewable technology generation option for urban areas.
- b. **Reliability** - With no fuel supply required and no moving parts, solar power systems are among the most reliable electric power generators, capable of powering the most sensitive applications, from space satellites to microwave stations in the mountains and other remote harsh environments. Solar panels typically carry warranties of 20 years or more.
- c. **Scalable and modular**- Solar power products can be deployed in many sizes and configurations and can be installed on a building roof or acres of field; providing wide power-handling capabilities, from microwatts to megawatts. The installation is quick and expanded to any capacity.
- d. **Universal Applications** - Solar PV is the only renewable energy technology that can be installed on a truly global scale because of its versatility and because it generates power under virtually all conditions, i.e. even in overcast light conditions
- e. **Peak Shaving** - Have a rapid response achieving full output instantly. The output of solar systems typically correlates with periods of high electricity demand where air conditioning systems create peak demands during hot sunny days. PV can shave peak load demand, when energy is most constrained and expensive and therefore can move the load off the grid and alleviate the need to build new peak generating capacity.

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- f. **Dual use** - Solar panels are expected to increasingly serve as both a power generator and the skin of the building. Like architectural glass, solar panels can be installed on the roofs or facades of residential and commercial buildings
- g. **Low Maintenance Cost** - It is expensive to transport materials and personnel to remote areas for equipment maintenance. Since photovoltaic systems require only inspection and occasional maintenance; these costs are usually less than with conventionally fuelled equipment alternatives.
- h. **Cost advantages** - Solar power systems lower your utility bills and insulate you from utility rate hikes and price volatility due to fluctuating energy prices. They can be used as building materials. They can increase character and value of the building. Purchase of a solar power system allows you to take advantage of available tax and financial incentives.

3.6. The Solar Cell:

3.6.1 Working Principle of Solar Cells:

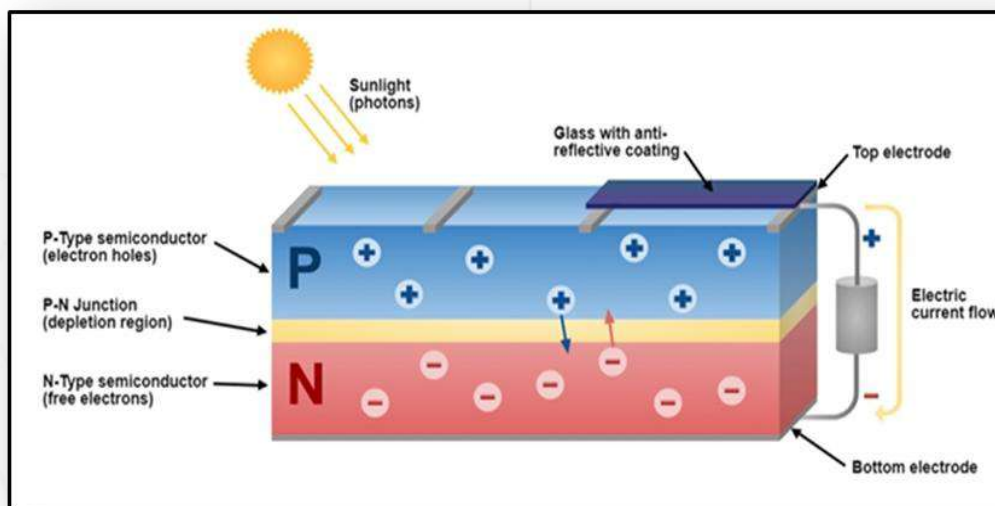


Fig. (3.6) Working Principle of Solar Cells.

How does a PV cell convert solar energy to electricity (Photovoltaic effect)?

Useful electricity can be directly generated by a solar cell, when it is exposed to electromagnetic radiation.

The principle behind that phenomenon is called the photovoltaic effect ^[58] These solar cells are composed of two different types of semiconductors—a p-type and an n-type—that are joined together to create a p-n junction. By joining these two types of semiconductors, an electric field is formed in the region of the junction as electrons move to the positive p-side and holes move to the negative n-side. This is, the generation of an electric potential difference at the junction of two different semiconductor materials,

This field causes negatively charged particles to move in one direction and positively charged particles in the other direction. Light is composed of photons, which are simply small bundles of electromagnetic radiation or energy When light of a suitable wavelength is incident on these cells, energy from the photon is transferred to an electron of the semiconducting material, causing it to jump to a higher energy state known as the conduction band. In their excited state in the conduction band, these electrons are free to move through the material, and it is this motion of the electron that creates an electric current in the cell. when this is exposed to light. The photovoltaic effect can be explained in three simple processes: (1) generation of charge carriers, (2) separation of the photo-generated charge carriers, and (3) collection of the photo-generated charge carriers.

First, charge carriers are generated when a photon is absorbed in a p-n junction. Those charge carriers are electron-hole-pairs. The charge carrier generation is possible when the photon energy (E_{ph}) is higher than the band gap energy (E_g) of the material ^[58] second, the excited electron-hole pair will try to find its equilibrium state by recombining. This means that the energy in the material will be lost. To avoid this, a semipermeable membrane, inside solar cell, collects the electrons into the n-type, and holes in the p-type Finally, the electrons are collected at the metallic electrodes of the solar cell. As a result, an electrical current is delivered by the solar cell, when this is connected to a load ^[64]. Figures (3.7) show the basic steps of the solar cell operation.

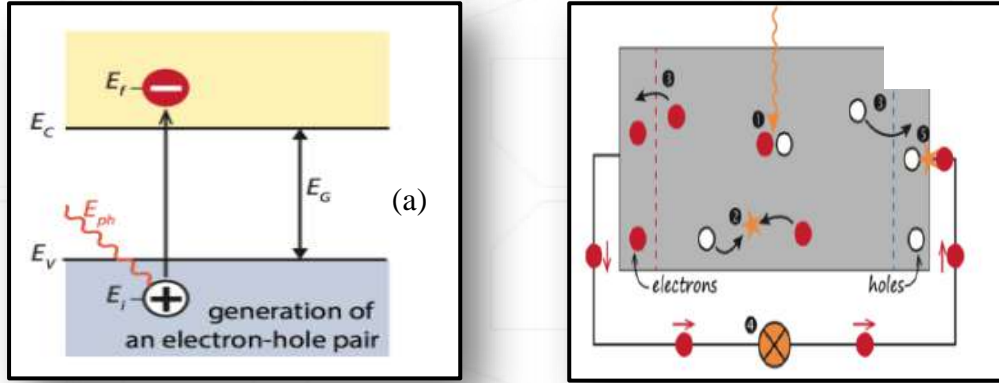


Fig. (3.7) (a): Illustration of the electron whole generation by a photon in a semiconductor with a.

bandgap energy E_G .^[58] (b): Illustration of the basic steps in a solar cell.

Figure (b).: Illustration of the basic steps in a solar cell.

1. Absorption of a photon generates an electron-hole pair.
2. Electron hole separation by a semipermeable membrane.
3. Electron-hole recombination.
4. Generated electric current.^[58]

1

3.6.2 The flow of electricity in a solar cell:

The movement of electrons, each carrying a negative charge, toward the front surface of the solar photovoltaic cell creates an imbalance of electrical charge between the cell's front and back surfaces. This imbalance, in turn, creates a voltage potential like the negative and positive terminals of a battery. Electrical conductors on the cell absorb the electrons. When the conductors are connected in an electrical circuit to an external load, such as a battery, electricity flows through the circuit.

The absorption of a photon can create an electron-hole pair. The mobile charge carriers resulting from absorption can alter the electrical properties of the material. One such effect, photoconductivity, is responsible for the operation of certain semiconductor photo detectors.

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3.7 Inside a photovoltaic cell:

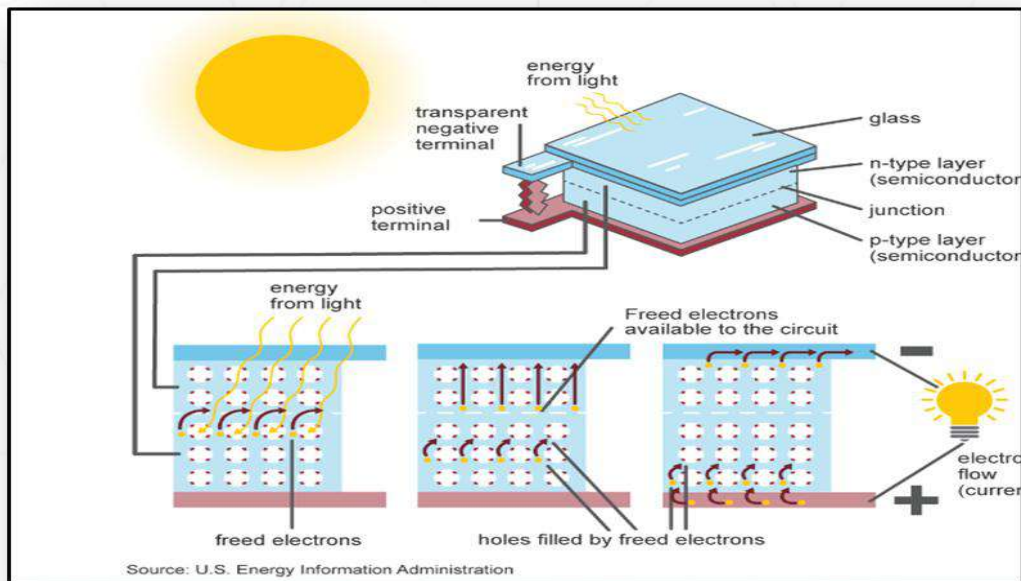


Fig. (3.8): Simplified representation of a solar cell.

3.7.1 External Parameters of Solar cells:

Solar cells are characterized by four main parameters: (1) the short-circuit current density, (2) the open circuit voltage, (3) the maximum power, and (4) the fill factor. Further, these parameters are tested at standard test conditions and can be represented in a current voltage (I-V) characteristic curve.

Short Circuit Current (J_{sc}):

The current density delivered by a solar cell at 0 V bias is defined as the short circuit current density J_{sc} . This current is generated when the electrodes of the solar cell are short circuited. This value highly dependent on the photon flux over the solar cell, the area and the material properties of solar cell ^[58].

Open Circuit Voltage (V_{oc} :)

The voltage under open circuit conditions of a solar cell is referred as the open circuit voltage^[58]. This value is the voltage at which no current flows through the external circuit. The V_{oc} depends on the material properties and photocurrent density. The V_{oc} value can be calculated using Eq. (3.1).

$$V_{oc} = \frac{kBT}{q} \ln \left(\frac{J_{ph}}{J_0} + 1 \right) \approx \frac{kBT}{q} \ln \left(\frac{J_{ph}}{J_0} \right) \quad (3.1)$$

where, $kB = 1.38 \times 10^{-23} \text{ J /K}$, is the Boltzmann's constant, $q = 1.602 \times 10^{-19} \text{ C}$, is the elementary charge, T is the cell's temperature in kelvin (K), J_{ph} is the photo-generated current density and J_0 is the saturation current. The approximation, in Eq. (3.1), is justified because $J_{ph} \gg J_0$ ^[58].

Maximum Power (P_{max}):

The maximum produced power P_{max} from a solar cell is the operational point of the solar cell at which $V \times I$ maximize. This point is where the solar cell can deliver its maximum electrical power at a certain level of irradiance.

Fill Factor (FF):

The fill factor is defined as the ratio between the maximum power generated by the solar cell and the product of the open-circuit voltage and short-circuit current^[64].

Although there are a number of technical parameters to evaluate the quality of any PV Modules, the Fill Factor is the quickest way for knowing the quality/grade of a particular PV Module. FF is not indicated by manufacturers on the datasheet. That is for a reason. Because when you seek that information, your manufacturer would know that they can't give you modules based on lower fill factor^[58]. as shown in Fig. (3.9).

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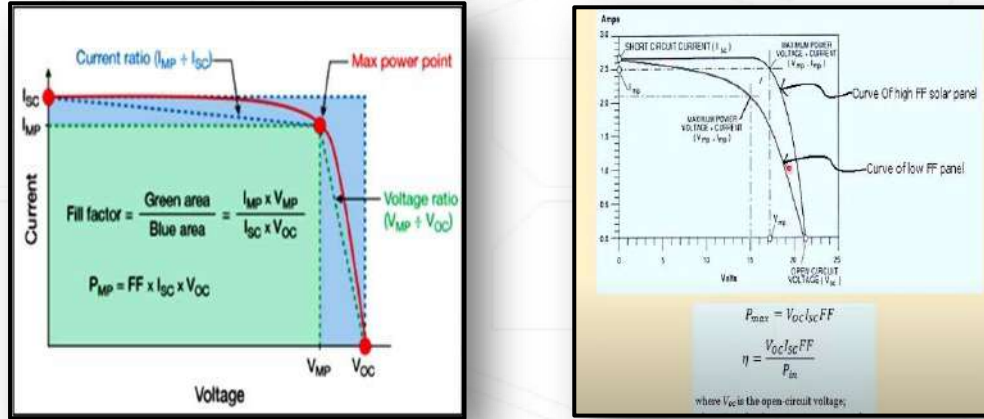


Fig. (3.9) Fill Factor (FF%) of a PV Modules is more important than Efficiency (%)

Where, $P_{max} = I_{mpp} V_{mpp}$ stands for the power at the maximum power point (MPP). The fill factor provides a relative quality index of the solar cell. For instance, the best crystalline silicon solar cell, has a $FF=0.846$, achieved by Yoshikawa ^[59]. For different technology, like *GaAs* solar cell, a $FF=0.89$ has been achieved. ^[57]

$$FF = \frac{P_{max}}{I_{sc} V_{oc}} \quad (3.2)$$

Solar cells performance (Efficiency):

The performance of a solar cell is evaluated by its efficiency. This parameter is equal to the ratio between the energy output delivered by the solar cell, and the input energy from the sun (I_{in}), as shown in Eq. (3.3). The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. The efficiency of a solar cell can significantly change for different temperature and irradiance conditions. Thus, the efficiency is measured under the standard test conditions. The highest efficiency record for a crystalline silicon solar cell is 26.6% ^[59].

$$\eta = \frac{P_{max}}{I_{in}} = \frac{I_{sc} V_{oc} FF}{I_{in}} \quad (3.3)$$

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PV Array:

Multiple PV strings are connected in parallel to form a Solar Array. Parallel connection increases the current, while voltage remains the same. The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an array. Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can plug into the existing infrastructure to power lights, motors, and other loads. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current. Solar arrays are typically measured by the electrical power they produce, in watts, kilowatts, or even megawatts.

PV Materials:

The vast majorities of commercially available PV modules are made from silicon, which is one of the earth's most abundant elements in the Earth's crust (after oxygen). Silicon's natural properties as a semiconductor are modified by two other elements, boron and phosphorus to create a permanent imbalance in the molecular charge of the material as in Figure (3.10).

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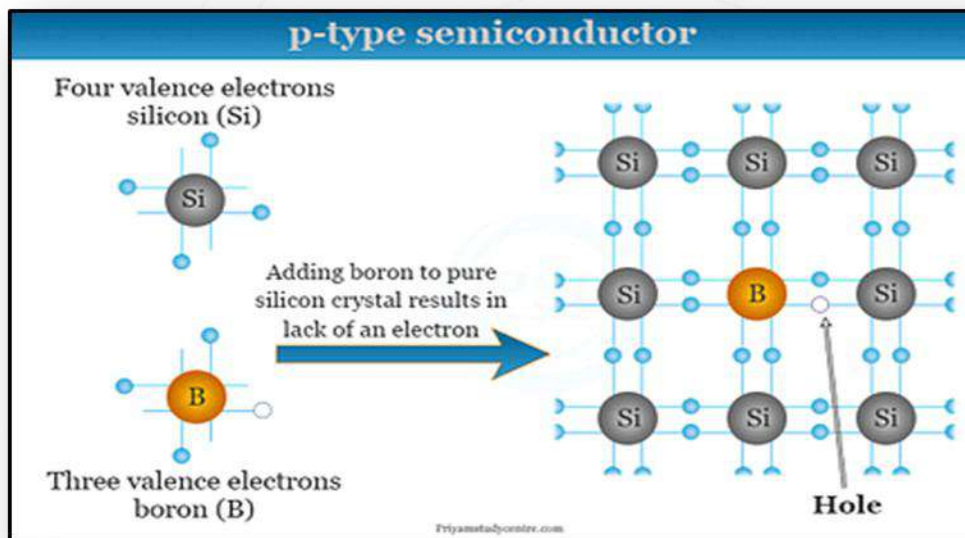
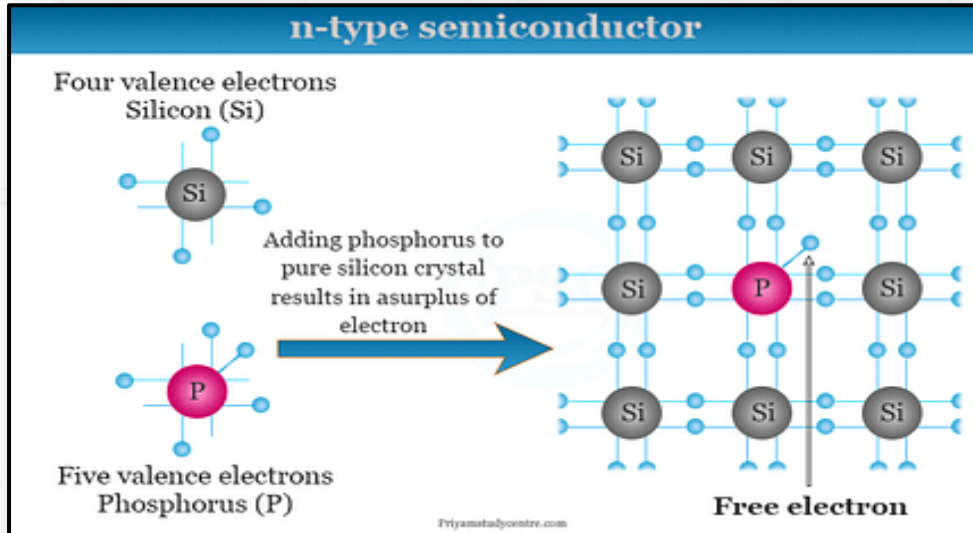


Image Source: <https://www.priyamstudycentre.com/2021/09/semiconductor.html>

Fig. (3.10). Doping of a pure silicon array. Silicon based intrinsic semiconductor becomes extrinsic when impurities such as Boron and phosphorus are introduced.

- A. 85 % of solar cell market.
- B. Life expectancy of >30 years.
- C. Energy payback in 2-8 years (positive).

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3.8 PV Types:

The three general types of photovoltaic cells made from silicon are in Fig. (3.11):

- Mono-crystalline Silicon – also known as single-crystal silicon.
- Poly-crystalline Silicon – also known as multi-crystal silicon.

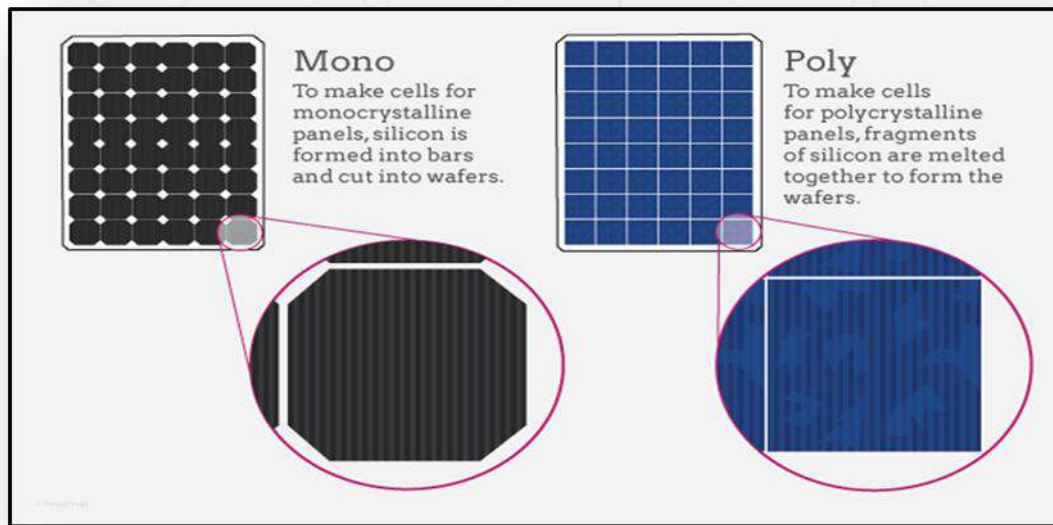


Fig. (3.11) PV Types.

- Thin Film Silicon.

3.9. Crystalline Cells:

Crystalline photovoltaic cells are made from silicon which is first melted, and then crystallized into ingots or castings of pure silicon. Thin slices of silicon called wafers, are cut from a single crystal of silicon (Mono-crystalline) or from a block of silicon crystals (Poly-crystalline) to make individual cells. The conversion efficiency for these types of photovoltaic cell ranges between 10% and 20%. Crystalline photovoltaic cells represent about 90% of the market today. Crystalline cells are divided into two categories: a. Monocrystalline silicon cells. b. Polycrystalline silicon cells.

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3.9.1 Monocrystalline PV:

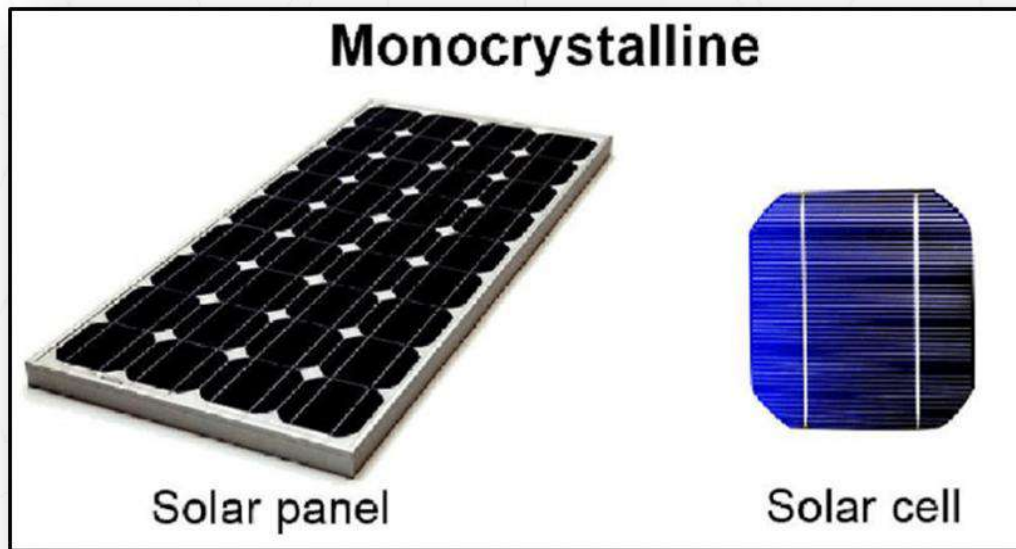


Fig. (3.12) Monocrystalline cell.

Monocrystalline cell comes from a single crystal ingot of high purity, with typical dimensions of 12.5 or 15 cm. The ingot has a cylindrical shape, which is cut into thin slices and made round, semi-round or square shapes. These cells are the most electrically efficient, which means they require less surface area than other cell types to produce an equivalent amount of power.

They also have a wide range of transparency options. Disadvantages are their higher costs, requirement for ventilation in order to maximize performance, and a distinctive geometric pattern. Monocrystalline cells are especially suitable for atrium roofs; partial vision glazing in façades, rooftop installations in houses and commercial sun shading or rooftop retrofits where installation area is limited and maximum electricity generation is desired. Commercial module efficiencies range around 14-19%.^[60]

Advantages of Mono-crystalline solar Cell:

- Monocrystalline solar panels have the highest efficiency rates since they are made out of the highest-grade silicon.
- The efficiency rates of mono-crystalline solar panels are typically 15-20%. Sun Power produces the highest efficiency solar panels on the U.S. market today. Their E20 series provide panel conversion efficiencies of up to 20.1%. Update (April, 2013): Sun Power has now released the X-series at a record-breaking efficiency of 21.5%.
- Monocrystalline silicon solar panels are space-efficient. Since these solar panels yield the highest power outputs, they also require the least amount of space compared to any other types.
- Mono-crystalline solar panel produce up to four times the amount of electricity as thin-film solar panels.
- Mono-crystalline solar panel live the longest. Most solar panel manufacturers put a 25-year warranty on their mono-crystalline solar panel.
- Tend to perform better than similarly rated poly-crystalline solar panel at low-light conditions.

Disadvantages of Mono-crystalline solar Cell:

- Mono-crystalline solar panels are the most expensive.
- From a financial standpoint, a solar panel that is made of poly-crystalline silicon (and in some cases thin-film) can be a better choice for some homeowners.
- If the solar panel is partially covered with shade, dirt or snow, the entire circuit can break down. Consider getting micro-inverters instead of central string inverters if you think coverage will be a problem. Micro-inverters will make sure that not the entire solar array is affected by shading issues with only one of the solar panels.
- The Czochralski process is used to produce mono-crystalline silicon. It results in large cylindrical ingots. Four sides are cut out of the ingots to make silicon wafers. A significant amount of the original silicon ends up as waste.
- Monocrystalline solar panels tend to be more efficient in warm weather.

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- Performance suffers as temperature goes up, but less so than polycrystalline solar panel. For most home owners' temperature is not a concern. ^[60]

3.9.2 Polycrystalline PV:

Silicon cells are formed by casting in a cuboid form ingot. The ingot is cut into bars and sliced into thin wafers (a thin sheet of semiconductor material), which in turn are used to create the cells. These cells are less efficient than monocrystalline;

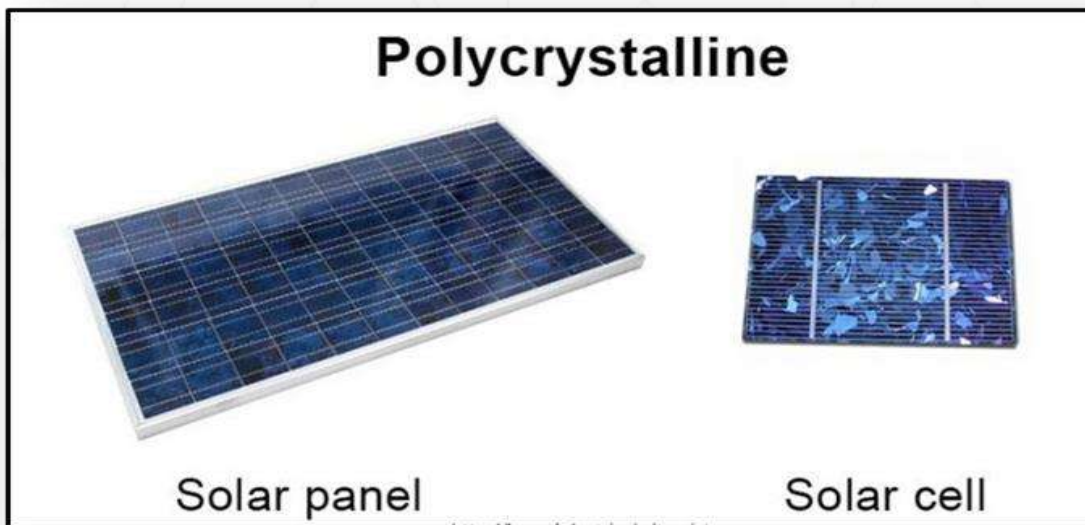


Fig. (3.13). Polycrystalline PV.

however, the lower cost per unit area and their distinctive appearance makes them a popular choice for relatively large, opaque installations. They have been used extensively in façade spandrel panels and sun shading elements on commercial buildings. Figure (3.14). Polycrystalline silicon differs from monocrystalline in terms of cost (due to the reduction of losses) and efficiency (due to the grain boundaries). The difference is small, but still leads to the need for larger cells (21 x 21cm) in order to reach the same efficiency levels. Commercial module efficiencies range around 13-16%.

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Fig. (3.14) Spandrel Panels.

Advantages of Poly-crystalline silicon Solar Panels:

- The process used to make poly-crystalline silicon is simpler and cost less. The amount of waste silicon is less compared to mono-crystalline.
- Poly-crystalline solar panel tend to have slightly lower heat tolerance than mono-crystalline solar panel. This technically means that they perform slightly worse than mono-crystalline solar panels in high temperatures.
- Heat can affect the performance of solar panel and shorten their lifespans. However, this effect is minor, and most homeowners do not need to take it into account.

Disadvantages of Poly-crystalline silicon Solar Panels:

- The efficiency of poly-crystalline-based solar panel is typically 13-16%. Because of lower silicon purity, poly-crystalline solar panels are not quite as efficient as mono-crystalline solar panel.
- Lower space-efficiency. You generally need to cover a larger surface to output the same electrical power as you would with a solar panel made of mono-crystalline silicon. However, this does not mean every mono-crystalline solar panel perform better than those based on poly-crystalline silicon.

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- Mono-crystalline and thin-film solar panels tend to be more aesthetically pleasing since they have a more uniform look compared to the speckled blue color of poly-crystalline silicon.

3.9.3 Thin-Film PV:



Fig. (3.15). Thin Film Solar Cell.

Thin film photovoltaics are produced by printing or spraying a thin semiconductor layer of PV material onto a glass, metal or plastic foil substrate. By applying these materials in thin layers, the overall thickness of each photovoltaic cell is substantially smaller than an equivalent cut crystalline cell, hence the name “thin film”. As the PV materials used in these types of photovoltaic cells are sprayed directly onto a glass or metal substrate, the manufacturing process is therefore faster and cheaper making thin film PV technology more viable for use in a home solar system as their payback time is shorter. However, although thin film materials have higher light absorption than equivalent crystalline materials, thin film PV cells suffer from poor cell conversion efficiency due to their non-single crystal structure, requiring larger sized cells. Semiconductor materials used for the thin film types of photovoltaic cell include:

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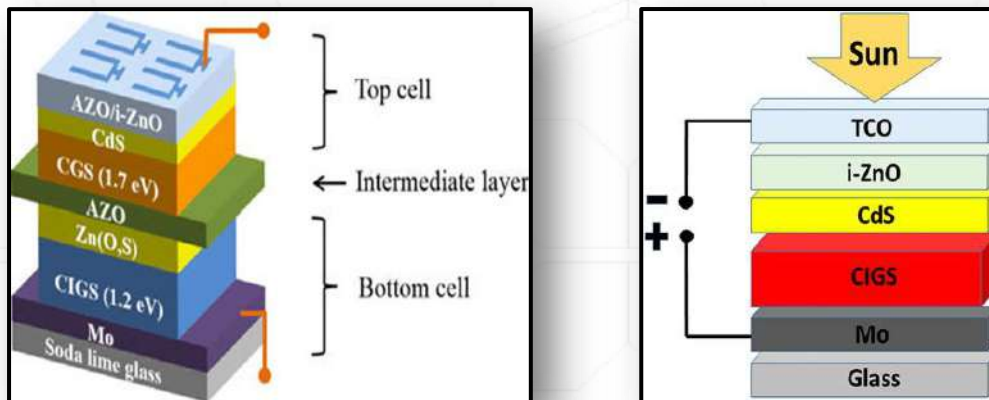


Fig.(3.16) Schematic of the CGS/CIGS monolithic tandem solar cell structure.

- Sadmium telluride (CdTe).
- Copper indium diselenide (CIS).
- c. Amorphous silicon (a-Si) .
- d. Thin film silicon (thin film-Si.)

Amorphous silicon is in commercial production while the other three technologies are slowly reaching the market. Amorphous silicon cells have various advantages and disadvantages. On the plus side, amorphous silicon can be deposited on a variety of low-cost rigid and flexible substrates such as polymers, thin metals and plastics as well as tinted glass for building integration.

However, on the minus side, the main disadvantage of amorphous silicon (a-Si) is its very low conversion efficiency ranging between 6 to 8% when new ^[61]

Of the different types of photovoltaic cell available, amorphous silicon has the highest light absorption of over 40 times higher than crystalline silicon. The advantage of this is that a much thinner layer of amorphous silicon material is required to make a thin film PV cell reducing manufacturing costs and price. Just to give a brief impression of what “thin” means, in this case, we’re talking about a thickness of 1 micrometer. With only 6 to 7% efficiency rate, these cells are less effective than crystalline silicon ones— but in current scenario, while a larger surface area is required for output, the cost of electricity per Watt peak is currently more attractive.

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3. 10 Steps to manufacture solar panels:

PV electricity production begins at the module level with semiconductor materials that convert sunlight directly into electricity. The semiconductor material varies, but crystalline-silicon (c-Si) semiconductors which have dominated U.S. and global PV module supply to date constitute about 95% of the modules sold today. Figure (3.17) illustrates the principal materials in the c-Si PV module supply chain. PV cells combined into modules and arrays of modules along with various balance-of-system (BOS) components comprise a PV system Figure (3.9).

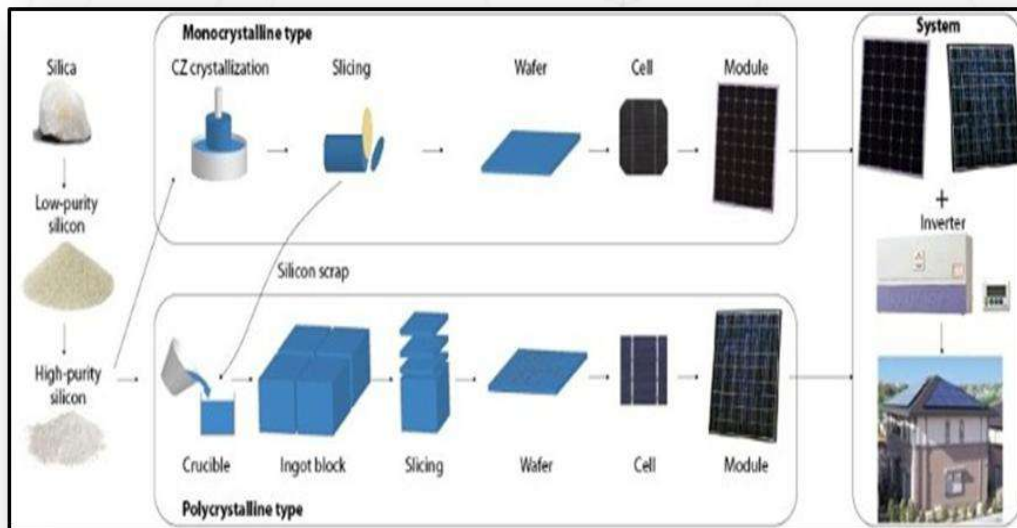


Figure (3.17)1. Principal components in the c-Si PV module supply chain and a common 2020 monocrystalline and polycrystalline silicon module with half-cut cells^[69]

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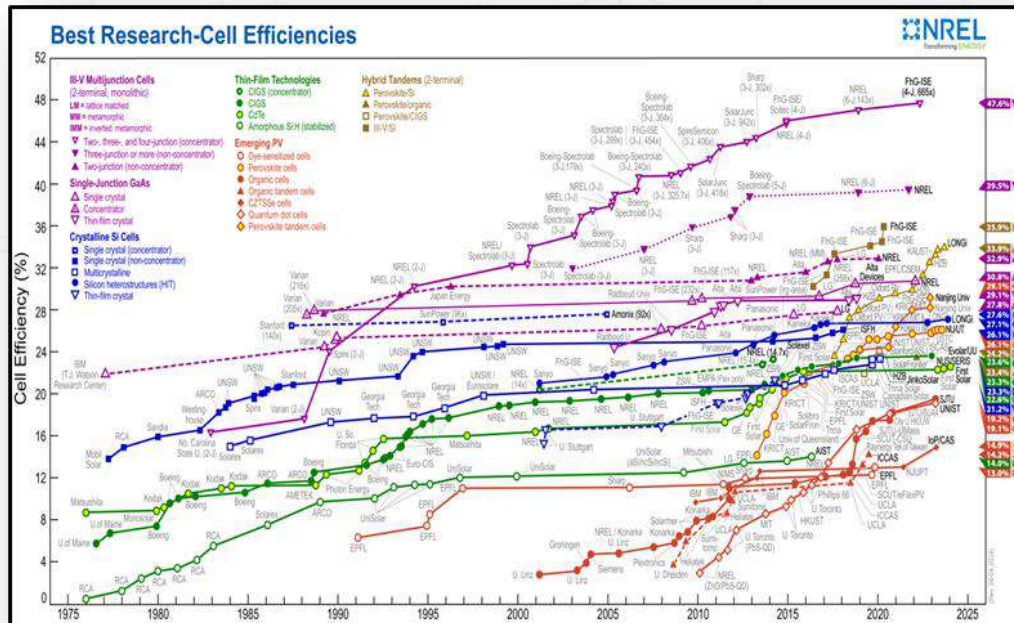


Fig. (3.18) NREL: chart for record efficiency solar cells.

3.11 PV System Components:

The key parts of a solar PV energy generation system are:

a. Photovoltaic array to collect sunlight as in Figure (3.19).

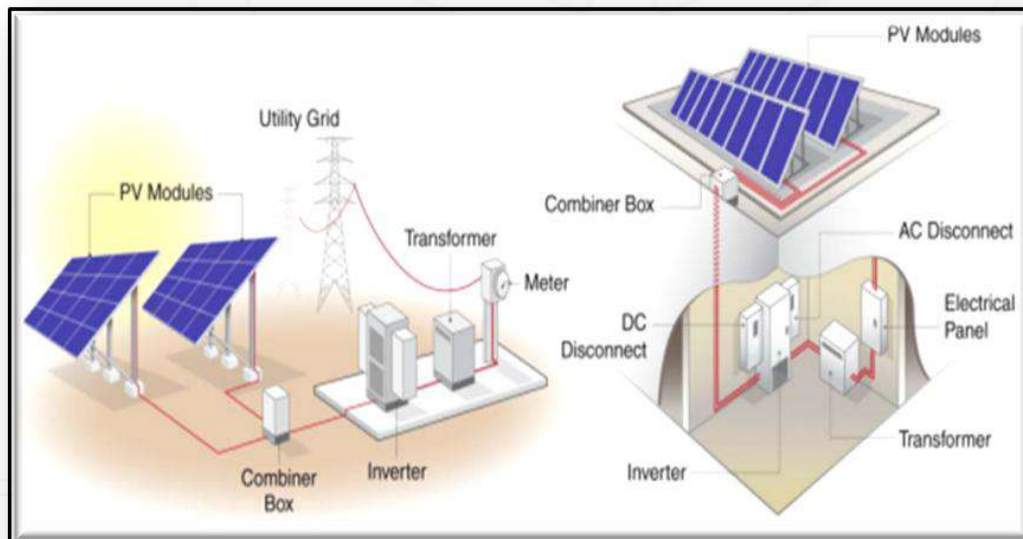


Figure (3.19). Principal components of PV systems for utility-scale ground-mount (left) and residential rooftop (right) applications.

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- Photovoltaic array to collect sunlight as in Figure (3.19).
- An inverter to transform direct current (DC) to alternate current (AC)
- A set of batteries and charge controller for stand-alone PV systems
- other system components.

All system components, excluding the PV modules, are referred to as the balance of system (BOS) components.



Fig. (3.20). PV System Components.

Array:

A PV Array is made up of PV modules, which are environmentally-sealed collections of PVS Cells—the devices that convert sunlight to electricity. The most common PV module that is 5- to 25 square feet in size and weighs about 3-4 lbs./ft².

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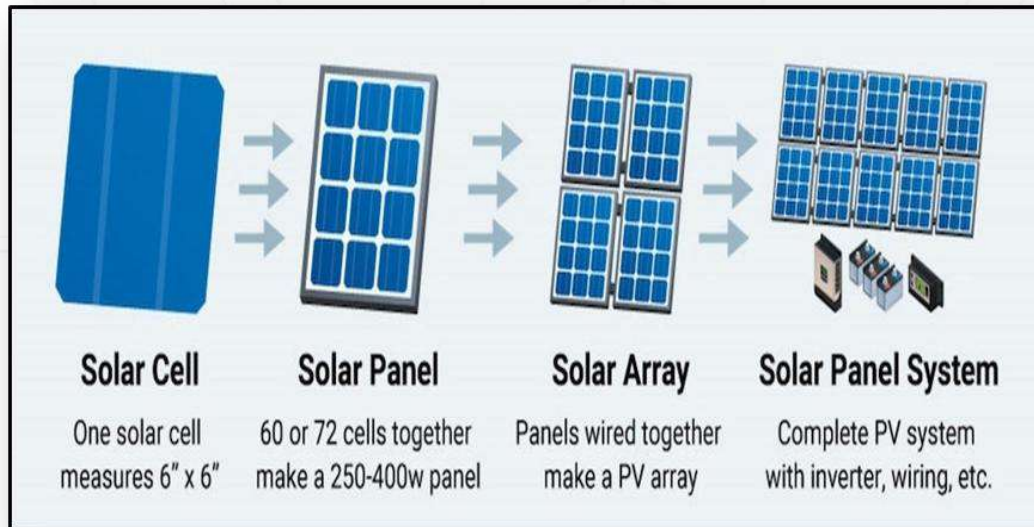


Fig (3.21) PV modules.

Often sets of four or more smaller modules are framed or attached together by struts in what is called a panel. This panel is typically around 20-35 square feet in area for ease of handling on This allows some assembly and wiring functions to be done on the ground if called for by the installation instructions.

Batteries:

Batteries consist of voltaic cells that are connected in series to provide a steady DC voltage at the output terminals Fig. (3.21). The voltage is produced by a chemical reaction inside the cell. Electrodes are immersed in an electrolyte, which forces the electric charge to separate in the form of ions and free electrons. Battery stores electric power for operation during nighttime or during extended periods of cloudy or overcast weather when the PV array by itself cannot supply enough power.

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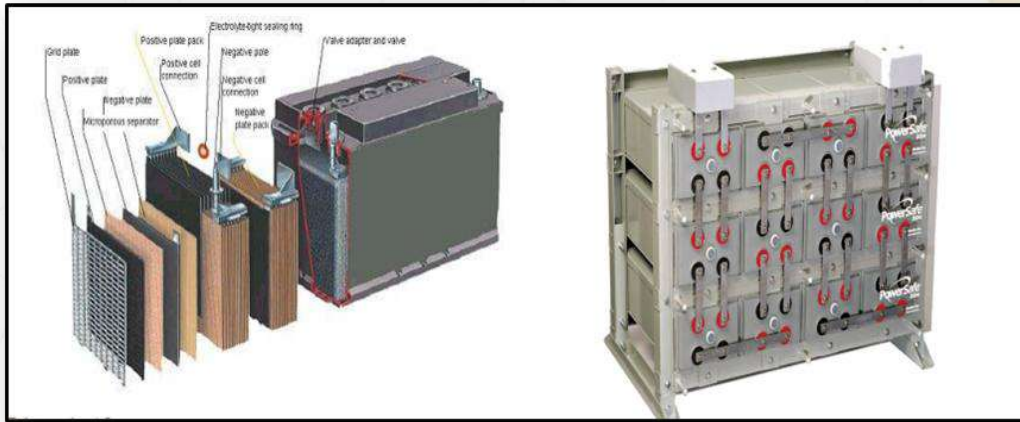


Fig. (3.22) Types of batteries.

The number of days the battery storage capacity is available to operate the electrical loads directly from the battery, without any energy input from the PV array is called days of “autonomy” in a standalone PV system. For common, less critical PV applications, autonomy periods are typically designed for between two and six days. For critical applications involving essential loads or public safety autonomy periods may be greater than ten days. Lead-acid or lithium-ion batteries are typically used.

Inverter:

The photovoltaic array and battery produce DC current and voltage. The purpose of an inverter is to convert the DC electricity to AC electricity used by your electrical appliances and/or exportable to the AC grid. Inverters are offered in a wide range of power classes ranging from a few hundred watts (normally for stand-alone systems), to several kW (the most frequently used range) and even up to 2,000 kW central inverters for large-scale systems.

Charge Controller:

Batteries are connected to the PV array via a charge controller. The charge controller protects the battery from overcharging or discharging. It can also provide information about the state of the system or enable metering and payment for the electricity used.

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Balance of System (BOS):

In addition to the PV modules, battery, inverter and charge controller there are other components required in a solar PV micro grid system; these components are referred to as Balance of Systems (BOS) equipment. The most common components are mounting structures, electricity meters, cables, power optimizers, protection devices, transformers, combiner boxes, switches, etc.

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CHAPTER 4

4.1. FACTORS AFFECTING PV MODULE PERFORMAN:

PV module's performance is directly related to the amount of sunlight it receives. If a PV module is shaded, even partially, its performance will be very poor. There are other factors that affect the output of a solar power system. These factors need to be understood so that the customer has realistic expectations of overall system output and economic benefits under variable weather conditions over time.

4.2 Environmental Factors:

4.2.1. Location:

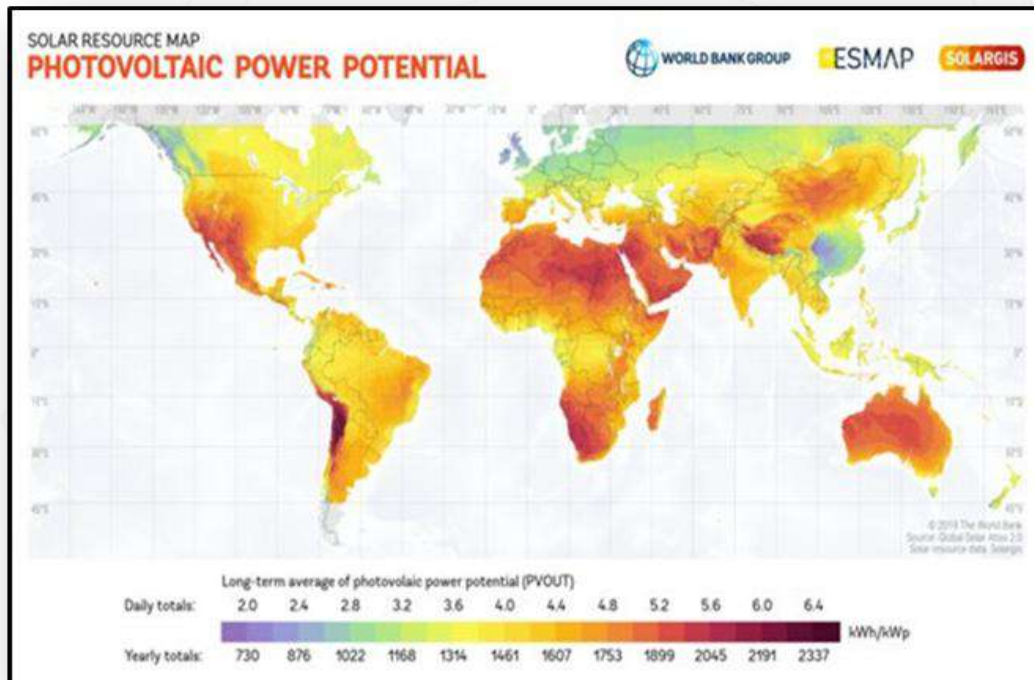


Fig (.4.1). Photovoltaic Electricity Potential.

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The top global solar power potential hotspots:

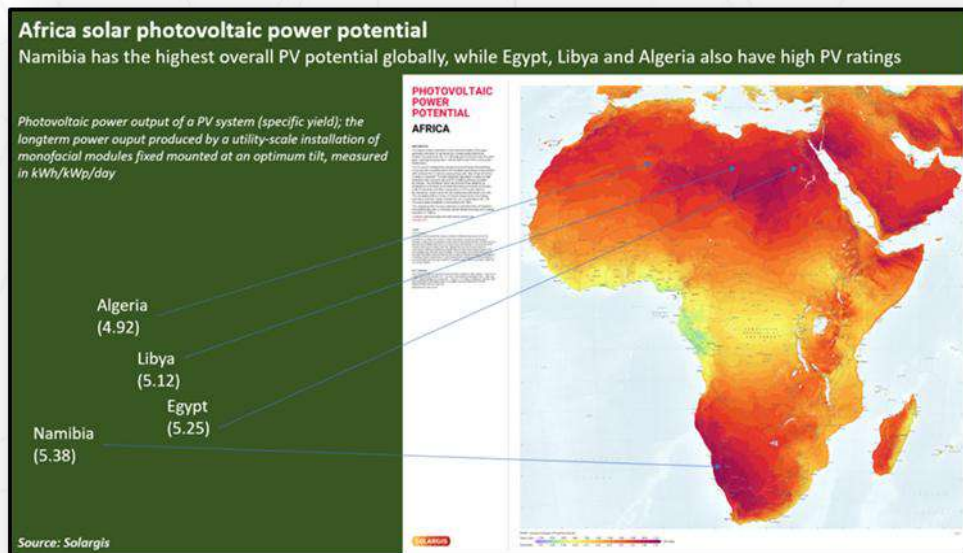


Fig. (4.2) Africa solar photovoltaic power potential.

Solar radiation is essentially a free resource available anywhere on Earth, to a greater or lesser extents as Fig. (4.2) shows. Solar PV power plants convert solar radiation into electricity. In the current era of global climate change, PV technology becomes an opportunity for countries and communities to transform or develop their energy infrastructure and step up their low-carbon.

When designing a PV system, location is the starting point. The amount of solar access received by the photovoltaic modules is crucial to the financial feasibility of any PV system. Latitude is a primary factor.

4.2.2. Solar Irradiance:

Occupying more than 99.68% ^[53] of the total mass in the solar system, the Sun, is the biggest and closet star to us. Nuclear fusion reactions, taking place in the core of the Sun, are responsible of all its energy. The Sun emits some of its energy to the entire universe as electromagnetic radiation. Ideally, the Sun can be considered as a black body with a temperature of 5800 K.

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Radiation: The transfer of energy via electromagnetic waves that travel at the speed of light Fig. (3.1). The velocity of light in a vacuum is approximately 3×10^8 m/s. The time it takes light from the sun to reach the Earth is 8 minutes and 20 seconds. Heat transfer by electromagnetic radiation can travel through empty space. anybody above the temperature of absolute zero ($-273.15C^0$) radiate energy to their surrounding environment. The many different types of radiation are defined by its wavelength. The electromagnetic radiation can vary widely as is clear in Fig. (3.1), (3.2).

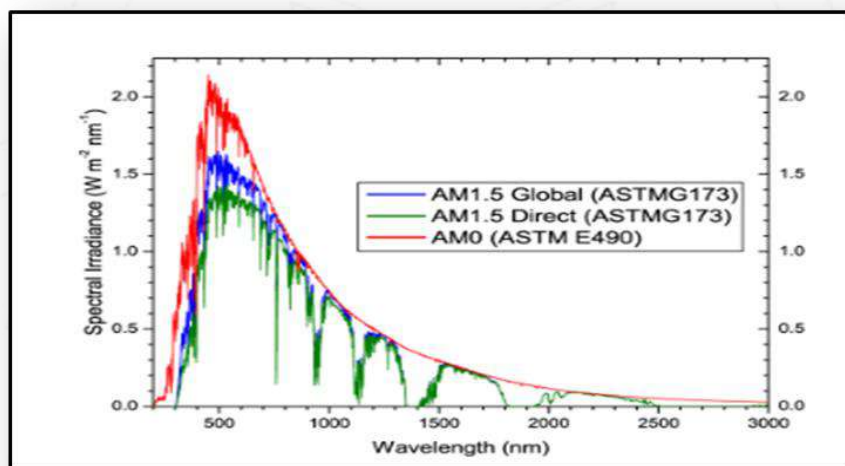


Figure (4.3): Standard Solar Spectra for space and terrestrial use.[3]

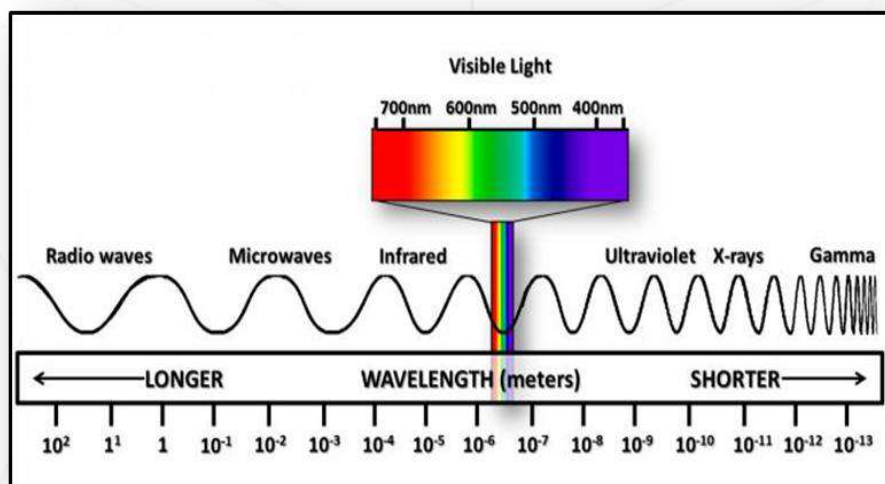


Fig (4.4) The electromagnetic spectrum. Courtesy of NASA.

The amount of solar radiation reaching the Earth at the outside of the atmosphere is approximately 1362 W/m^2 [47]. When the solar radiation penetrates the Earth's atmosphere, it gets attenuated. The air and dust in the atmosphere are responsible of the solar irradiance reduction. Also, the relative position between the zenith angle. [46] Earth and the Sun, highly influence the intensity of solar irradiance. This reduction in solar irradiance can be quantified. by using the concept of the Air Mass (AM). For space applications, the air mass coefficient is referred as AM0. The reduced spectral illumination after traveling through the atmosphere, in a plane perpendicular to the Sun's direction is defined as AM1.0. These spectral conditions change by the angle θ with the zenith as illustrated in figure (3.3).

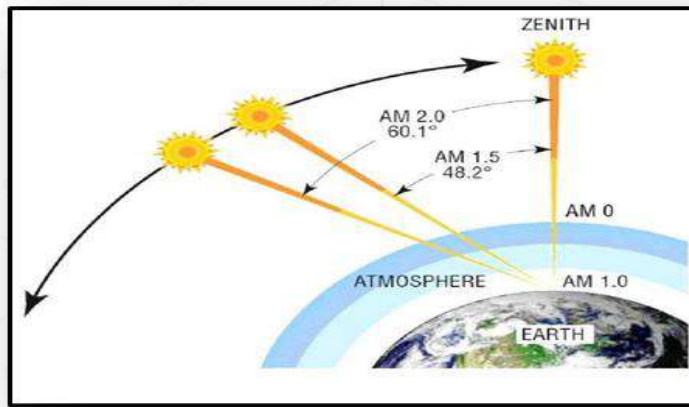


Fig. (4.5). Spectral conditions in units of Air Mass changing with the zenith angle. [56]

The actual amount of solar radiation over a specific location in the Earth's surface is extremely variable. Thus, some reference conditions have been established for evaluation and comparison purposes, of solar cells. These conditions include spectrum, intensity and temperature with values of: AM1.5 spectrum, 1000 W/m^2 and a cell temperature of 25°C . The variations of the solar spectrum are important for the design and optimization of solar cells. For a different wavelength region in the solar spectrum, a different solar cell technology might be more suitable, based on the band gap energy of the photovoltaic active material. Also, an understanding of the solar irradiance availability is important for an optimal design of a photovoltaic system.

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Solar Irradiance is a measure of how much sunlight intensity or power in Watts per square meter falling on a flat surface or you are getting at your location. Because weather conditions are somewhat similar over the years, it is possible to predict the average monthly and annual energy production of a system using historic, standardized weather data. see fig. (4.3).

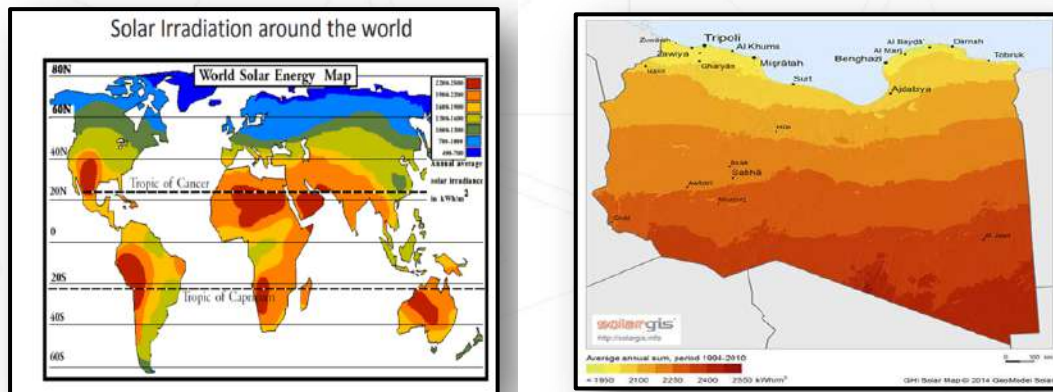


Fig. (4 6) Global horizontal irradiation of solar radiation in Libya (GSA, 2020).

There are maps available of solar resources showing how much energy reaches the surface of panels. The data is presented in standardized maps that show how many standard sunshine hours can be exacted over a month or a year. It expressed by term “solar insolation”.

4.2.3. Solar Insolation:

Solar insolation is a measure of solar irradiance reaches a PV surface at any given time. Solar energy available in a given location is expressed as $\text{kWh/m}^2/\text{day}$. This is commonly referred as Peak Sun Hours (PSH). For example, if solar radiation for a location is $5\text{kWh/m}^2/\text{day}$ then PSH for that location will be 5 hours. Now, if you install 1kW solar panel on that location, it will produce $1\text{kW} \times 5\text{h} = 5\text{kWh}$ energy per day without considering any losses.

More intense sunlight will result in greater module output. Lower sunlight levels result in lower current output. Voltage is not changed appreciably by variations of sunlight intensity. The map below Fig (4.3). shows the amount of solar energy in hours, available each day on an optimally tilted surface during the worst months of the year to generate electricity (based on accumulated worldwide solar insolation data). This is very useful because it allows you to calculate the energy generation of your solar system.

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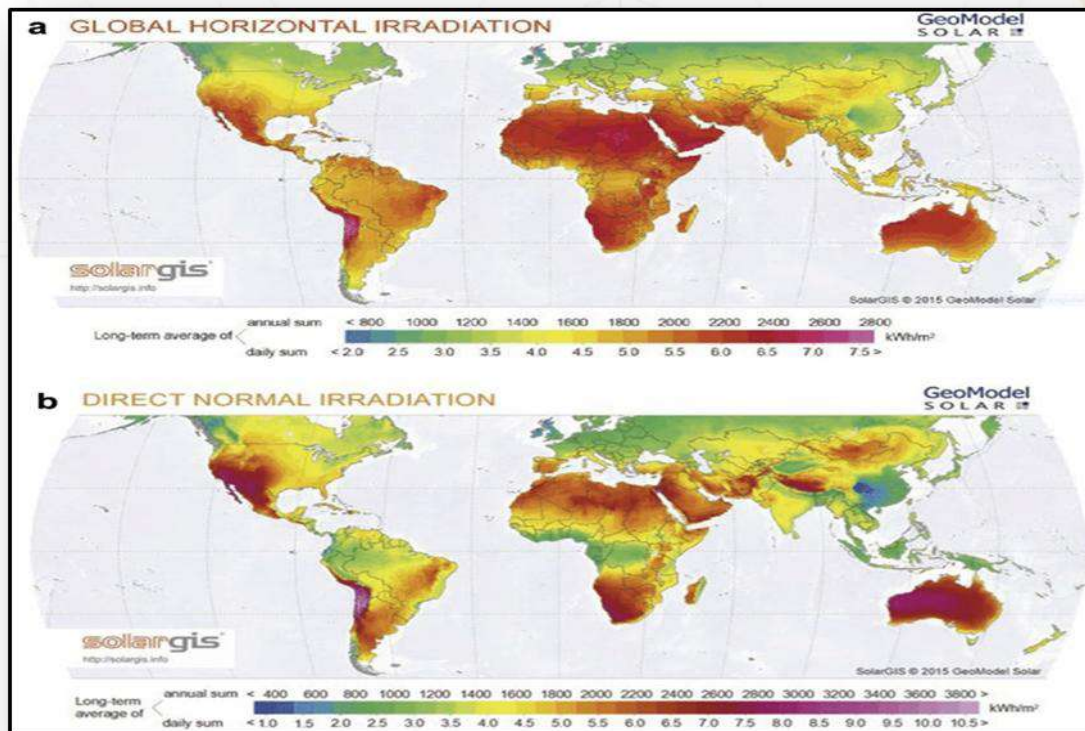


Fig (4.7) a: World Solar Global Horizontal Irradiation Map with indicated regions showing the long-term average of their annual and daily sum in kWh (m²). Source: [36]. b: World Solar Direct Normal Irradiation Map with indicated regions showing the long-term average of their annual and daily sum in kWh (m²). Source: [70].

Statistical estimations of average daily insolation levels for specific locations are commonly used in the PV design process and measured as kilowatt-hours per square meter per day (kWh/m²/day).

4.2.4. Electricity Generation V/s:

The Sun Hours Available per Day Several factors influence how much sun power your modules will be exposed to: a. When you will be using your system summer, winter, or year-round. b. Typical local weather conditions c. Fixed mountings vs. trackers d. Location and angle of PV array.

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4.2.5. Air Mass:

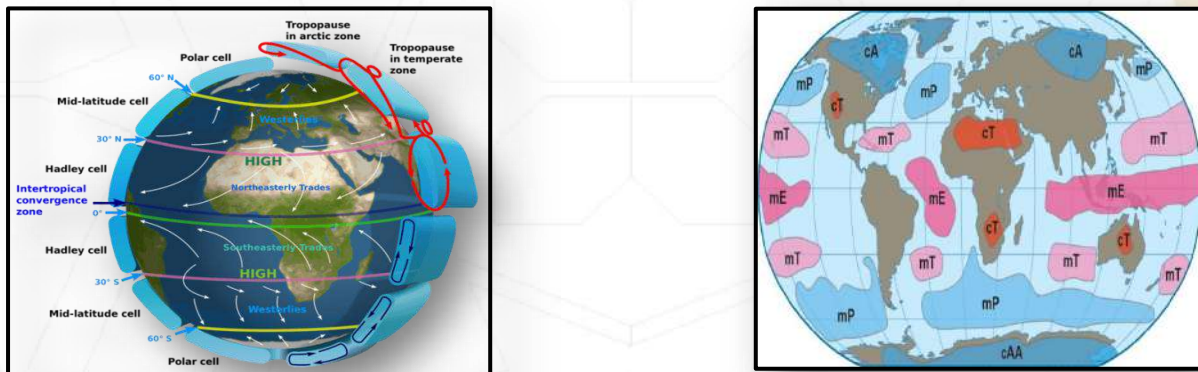


Fig. (4.8). Distribution of the source areas of the main air masses today (modified from [6]). cA is continental Arctic air, cAA is continental Antarctic air, mP is maritime Polar air, mT is maritime Tropical air, CT is continental Tropical air and mE is maritime Equatorial air. Air mass refers to “thickness” and clarity of the air through which the sunlight passes to reach the modules (sun angle affects this value). The standard is AM (1.5).

4.2.6. Sun Angle:

And PV Orientation The direction that a solar panel faces is referred to as its orientation. The orientation of the solar array is very important as it affects the amount of sunlight hitting the array and hence the amount of power the array will produce.

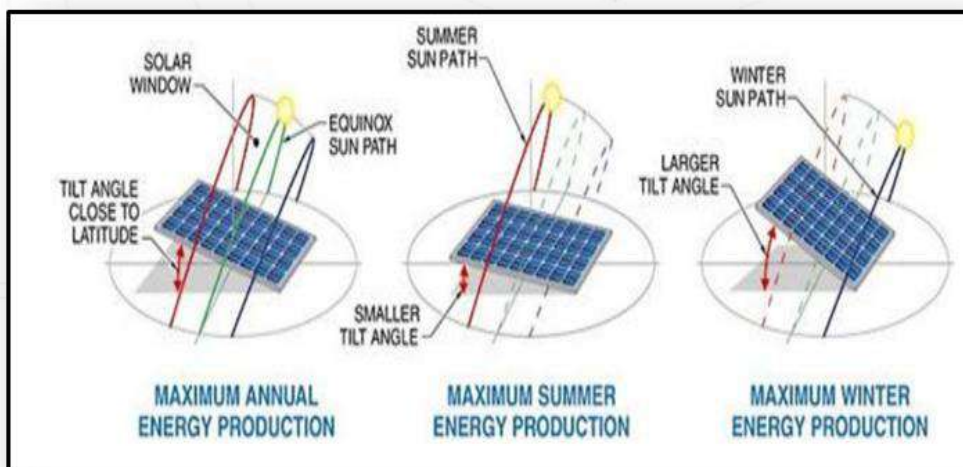


Fig. (4.9) Sun Angles.

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4.2.7 Tilt Angle:

The orientation generally includes the direction the solar module is facing (i.e. due south) and the tilt angle which is the angle between the base of the solar panel and the horizontal. The amount of sunlight hitting the array also varies with the time of day because of the sun's movement across the sky See Fig.(4.10).

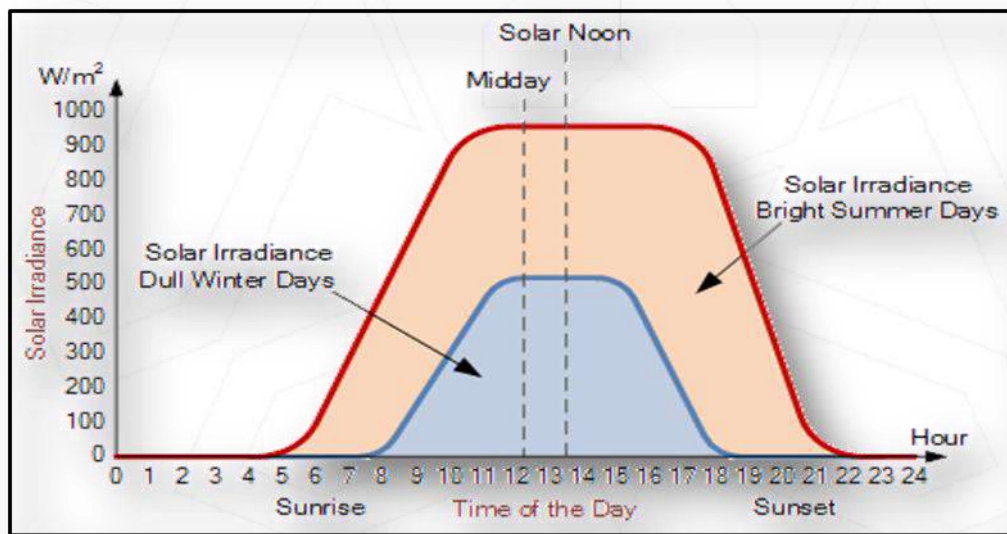


Fig. (4.10). Graph of Solar Irradiation During the Day.

Solar modules should be installed so that as much radiation as possible is collected. Ideally, the PV installations on the North of the equator perform optimally when oriented to the South and tilted at an angle 15 degrees higher than the site latitude. If the PV array is mounted on a where it is difficult for the panels to face the South, then it can be oriented to the East or West but under no circumstances to the North as its efficiency will be then very limited. The highest efficiency of a PV module or peak power occurs when its surface is perpendicular to the sun's rays. As the rays deviate from perpendicular, more and more of the energy is reflected rather than absorbed by the modules.

Most PV systems are mounted in a fixed position and cannot follow the sun throughout the day. It is possible to improve the output by installing PV modules on trackers to follow the sun from east to west during the day (single-axis trackers), and from north to south during seasonal changes (dual-axis trackers). This can be expensive, so it is not common practice for most PV.

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applications. PVs should be tilted toward the sun's average elevation, equal to the latitude of the array's location, to capture most of the solar energy throughout a year. For example, a system used throughout the year at latitude of 25° can have a tilt angle of 15° to 35° for maximum amount of electricity over a year. So, for example, if the average solar energy which falls on a surface during the summer months is 800 W/m^2 and is available for a full 8 hours per day, the daily amount of solar irradiance received during the summer months will be: $800 \text{ W/m}^2 \times 8 \text{ hours} = 6400 \text{ Wh/m}^2$ or 6.4 kWh/m^2 .

Thus, from above, we can see that if 1 kWh/m^2 is equal to one Peak Sun Hour (PSH), then 6.4 kWh/m^2 is equal to 6.4 peak sun hours, or 6.4 PSH.

4.2.8. Shading:



Fig. (4.11). The affects shade on Solar Panels

Shading may be one of the most important parameters for energy loss in a PV array. Even the partial-shading of one cell of a 36-cell module can reduce the power output significantly, as shown in figure (4.12). Potential shading sources can be trees and bushes, neighboring buildings and self-shading by the multiple rows of modules itself.

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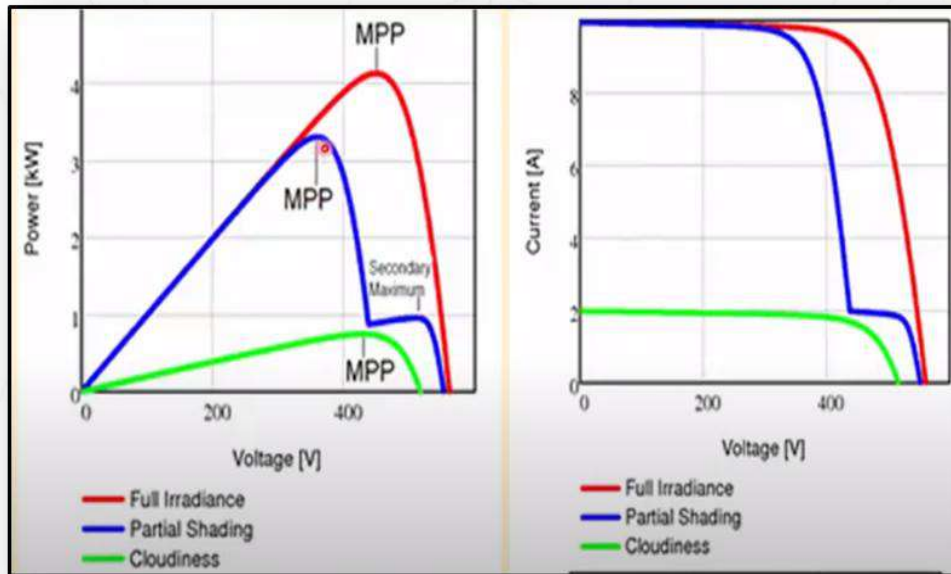


Fig. (4.12) The affects shade on Solar Panels.

Calculations need to be done to find the minimum distance between PV Array rows to avoid winter mid-day shading. The general rule of thumb is to locate the array at a distance away from the object that is at least twice the height of the object. This will ensure that the object will not cast a shadow for 4 hours either side of solar noon. As a rule, with lower tilt angle, there is less shading, and the area can be better exploited. However, in that case, the solar yield drops throughout the year. For this reason, a tilt angle of 15° is usually chosen. Thin film PV modules are more tolerant to partial shading than crystalline silicon PV modules.

4.3 Electrical Characteristics:

The type of solar power produced by a photovoltaic solar cell is called direct current or DC the same as from a battery. Most photovoltaic solar cells produce a “no load” open circuit voltage of about 0.5 to 0.6 volts when there is no external circuit connected. This outputs voltage (V_{OUT}) depends very much on the load current (I) demands of the PV cell. For example, on very cloudy day the current demand would be low and so the cell could provide the full output voltage, V_{OUT} but at a reduced output current. But as the current demand of the load increases a brighter light (solar radiation) is needed at the junction to maintain a full output voltage, V_{out} . etc.

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Most commercially available photovoltaic solar cells have solar power ratings which indicate the maximum deliverable solar power, P_{max} that the cell can provide in watts and is equal to the product of the cell voltage V multiplied by the maximum cell current I and is given as:

$$P_{max} = V_{out} \times I_{max}$$

Where: P is in Watts, V is in Volts, and I is in Amperes.

Various manufacturers refer to a PV cells output power at full sun as its: “maximum output power”, “peak power”, “rated power”, “maximum power point” or other such terms but they all mean the same.

4.3.1. Photovoltaic I-V Characteristics Curves (PV System):

A photovoltaic system, often known as a PV system or a solar power system, is an electric power system that uses photovoltaics to provide usable solar electricity. The primary energy source is the solar irradiation available at the site. At a given voltage, the solar cell produces the most electricity. The current–voltage and power–voltage characteristics are shown in Figure (4.13). It clearly indicates that the power curve has a point of maximum power, which is referred to as the 'maximum power point,' or MPP [62].

Manufacturers of the photovoltaic solar cells produce current-voltage (I-V) curves, which gives the current and voltage at which the photovoltaic cell generates the maximum power output and are based on the cell being under standard conditions of sunlight and temperature with no shading. Table (4.1). shows that. The Solar Cell I-V Characteristic Curves shows the current and voltage (I-V) characteristics of a particular photovoltaic (PV) cell, module or array. It gives a detailed description of its solar energy conversion ability and efficiency.

Trina Solar The power behind the panel	
TSM-280PA14	
Made in China	
Maximum Power (P_{max})	280W $\pm 5\%$
Maximum Power Voltage (V_{mp})	36.01V
Maximum Power Current (I_{mp})	7.78A
Open Circuit Voltage (V_{oc})	44.44V
Short Circuit Current (I_{sc})	8.45A
Maximum System Voltage	DC600V
Maximum Series Fuse	15A
Minimum Bypass Diode	15A
Fire Rating	Class C
For field connections, use minimum NO. 12AWG copper wires insulated for a minimum 90°C	
Electrical Rating At STC AM=1.5 IRRADIANCE=1000W/m ² Temp.=25°C	
<div style="display: flex; justify-content: space-between;"> <div> (Photovoltaic Module) LISTED E306515 </div> <div> Electrical Hazard This module produces electricity when exposed to light. Follow all applicable electrical safety precautions. </div> </div>	
www.trinasolar.com	

Fig. (4.13) panel properties.

Knowing the electrical I-V characteristics (more importantly P_{max}) of a solar cell, or panel is critical in determining the device's Output performance and solar efficiency. Solar Cell I-V Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarising the relationship between the current and voltage at the existing conditions of irradiance and temperature. I-V curves provide the information required to configure a solar system so that it can operate as close to its optimal peak power point (MPP) as possible

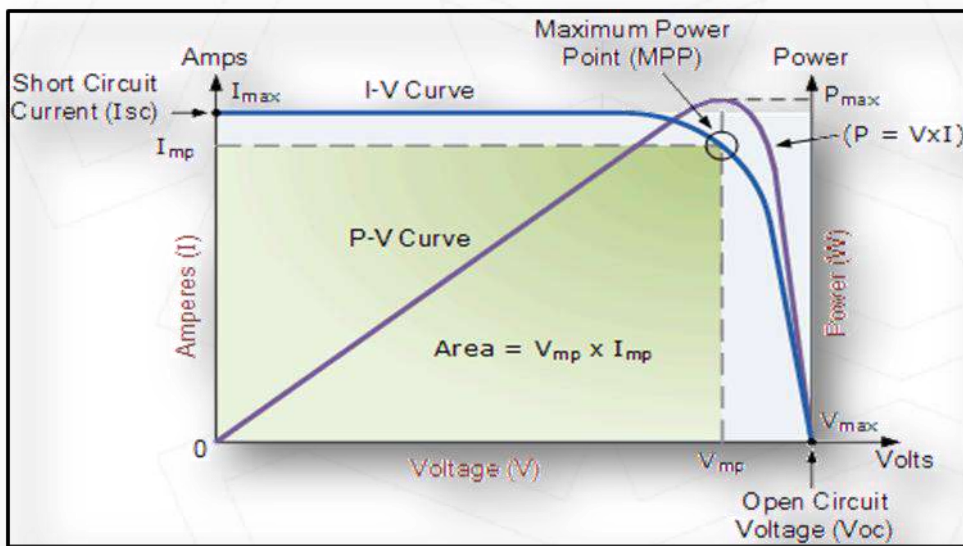


Fig (4.14) Current–voltage and power–voltage solar cell characteristics, showing MPP [49].

The above graph (4.16). shows the current-voltage (I-V) characteristics of a typical silicon PV cell operating under normal conditions. The power delivered by a single solar cell or panel is the product of its output current and voltage ($I \times V$). If the multiplication is done, point for point, for all voltages from short-circuit to open-circuit conditions, the power curve above is obtained for a given radiation level.

With the solar cell open-circuited, that is not connected to any load, the current will be at its minimum (zero) and the voltage across the cell is at its maximum, known as the solar cells open circuit voltage, or V_{oc} . At the other extreme, when the solar cell is short circuited, that is the positive and negative leads connected together,

the voltage across the cell is at its minimum (zero) but the current flowing out of the cell reaches its maximum, known as the solar cells short circuit current, or I_{sc} . Then the span of the solar cell I-V characteristics curve ranges from the short circuit current (I_{sc}) at zero output volts, to zero current at the full open circuit voltage (V_{oc}). In other words, the maximum voltage available from a cell is at open circuit, and the maximum current at closed circuit. Of course, neither of these two conditions generates any electrical power, but there must be a point somewhere in between where the solar cell generates maximum power.

However, there is one particular combination of current and voltage for which the power reaches its maximum value, at I_{mp} and V_{mp} . In other words, the point at which the cell generates maximum electrical power and this is shown at the top right area of the green rectangle. This is the “maximum power point” or MPP. Therefore, the ideal operation of a photovoltaic cell (or panel) is defined to be at the maximum power point. The maximum power point (MPP) of a solar cell is positioned near the bend in the I-V characteristics curve. The corresponding values of V_{mp} and I_{mp} can be estimated from the open circuit voltage and the short circuit current: $V_{mp} \cong (0.8-0.90) V_{oc}$ and $I_{mp} \cong (0.85-0.95) I_{sc}$. Since solar cell output voltage and current both depend on temperature, the actual output power will vary with changes in ambient temperature^[49].

4.3.2 Solar Intensity:

The amount of sunlight falling onto the face of the PV cell affects its output. The more sunlight entering the cell, the more current it produces. The voltage will remain the same. Figure below (4.15). shows that under different test conditions, when day light is 1000 W/m^2 , the power out from the PV module varies in proportion.

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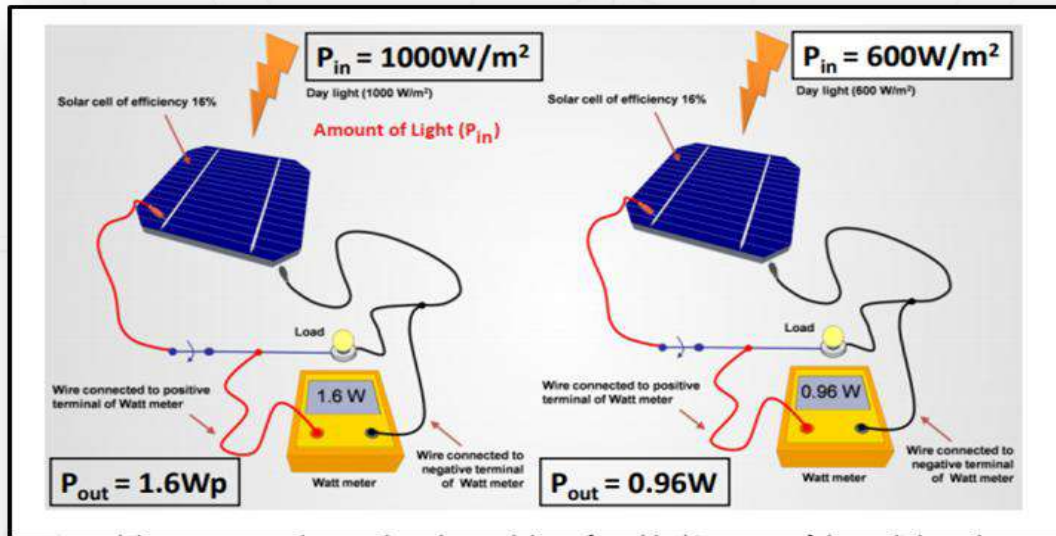


Fig. (4.15) Solar Intensity

Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing output. Although, rigorous maintenance will clean off the dirt and dust regularly, it is more realistic to estimate system output considering the reduction due to dust buildup in the dry season. A typical annual dust reduction factor to use is 93% or 0.93. So, the “100- watt module” operating with some accumulated dust may operate on average at about 79 Watts (85 Watts x 0.93 = 79 Watts).

4.3.3. Wiring Solar Panels in a Series:

Circuit Connect the positive terminal of the first solar panel to the negative terminal of the next one. Figure (4.16). Example: If you had 4 solar panels in a series and each was rated at 12 volts and 5 amps, the entire array would be 48 volts at 5 amps.

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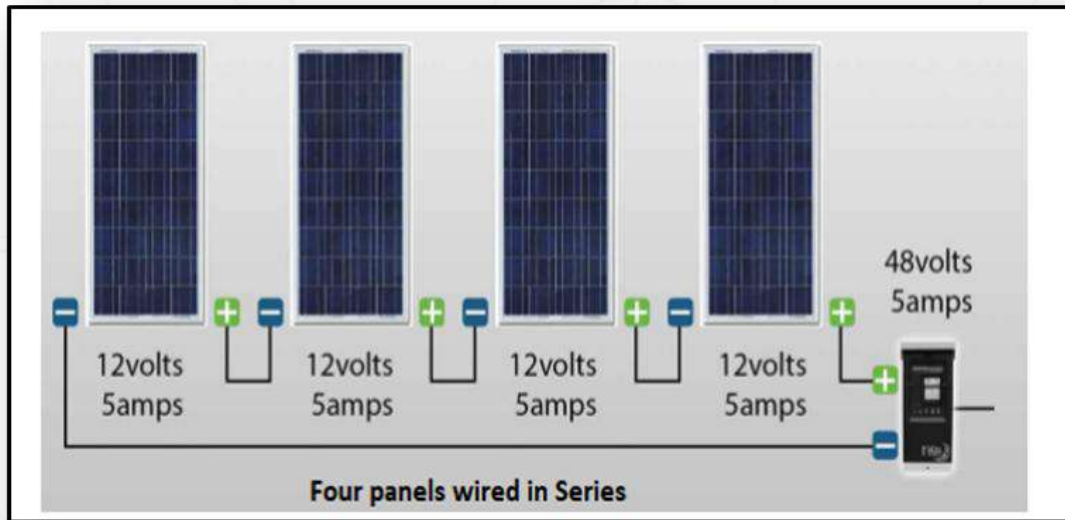


Fig. (4.16) panels wired in series.

4.3.4 Wiring Solar Panels in a Parallel:

To wire solar panels in parallel, connect all of the positive terminals on each panel together and then do the same for the negative terminals as it can be seen in (fig.4.17).

The resulting current will be the sum of all of the panel amperages in the parallel array. However, the total voltage will be equal to the output voltage of a single panel. Example: If you had 4 solar panels in parallel and each was rated at 12 volts and 5 amps, the entire array would be 12 volts at 20 amps.

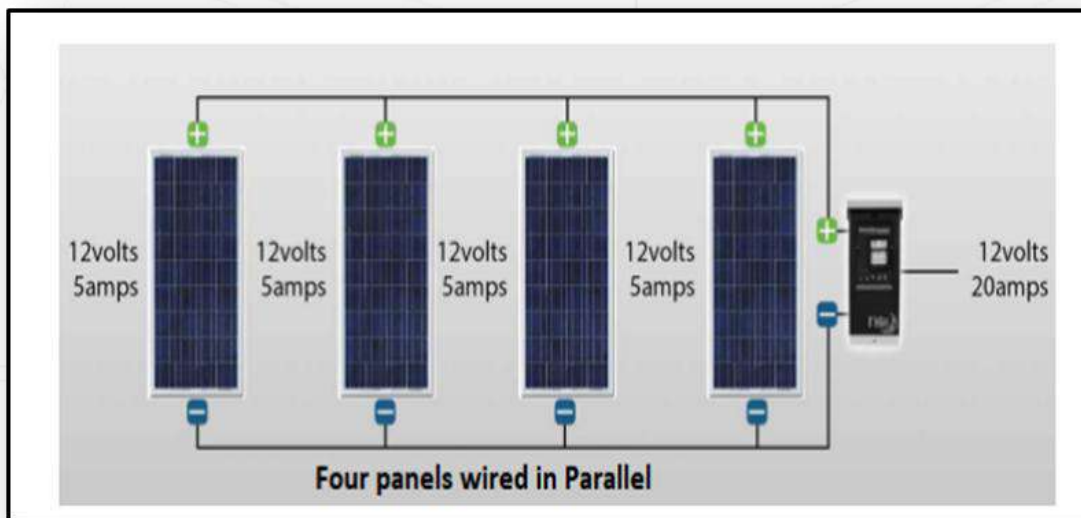


Fig. (4.17) panels wired in parallel.

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4.4 Performance degradation over life cycle:

The performance of a PV module will decrease over time. The degradation rate is typically higher in the first year upon initial exposure to light and then stabilizes. Factors affecting the degree of degradation include the quality of materials used in manufacture, the manufacturing process, the quality of assembly and packaging of the cells into the module, as well as maintenance levels employed at the site. Generally, degradation of a good quality module is about 20% during the module life of 25 years @ 0.7% to 1% per year.

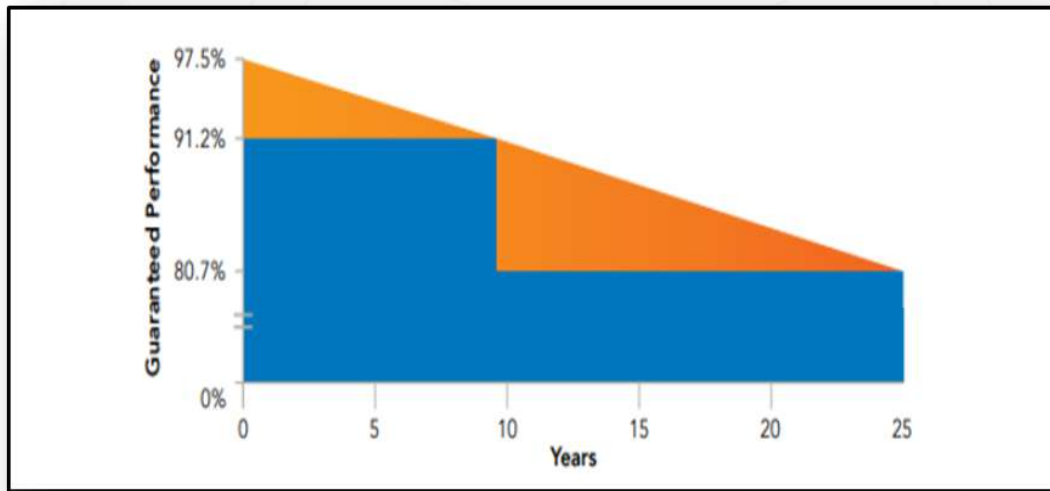


Fig. (4. 18) PV module degradation

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CHAPTER 5

5.1. History of Water Electrolysis:

Water electrolysis was first demonstrated in 1789

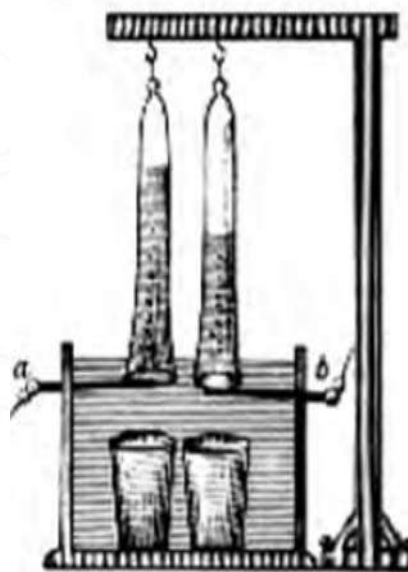


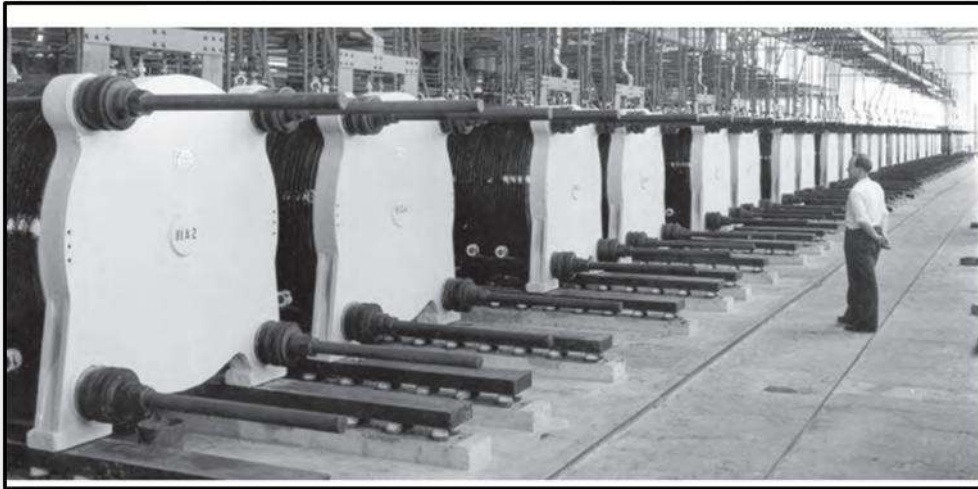
Fig. (5.1) Ritter's electrolysis apparatus.

by the Dutch merchants Jan Rudolph Deiman and Adriaan Paets van Troostwijk using an electrostatic generator to produce an electrostatic discharge between two gold electrodes immersed in water ^[81]. Later developments by Johann Wilhelm Ritter exploited Volta's battery technology and allowed separation of the product gases fig (5.2) ^[63]. Almost a century later, in 1888 a method of industrial synthesis of hydrogen and oxygen via electrolysis was developed by the Russian engineer Dmitry Lachinov ^[83] and by 1902 more than 400 industrial water electrolyzers were in operation ^[64].

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Early electrolyzers utilized aqueous alkaline solutions as their electrolytes, and this technology persists to this day. A more recent development in water electrolysis is the proton exchange membrane process, first described in the mid-1960s by General Electric as a method for producing electricity for the Gemini Space Program ^[89], and later adapted for electrolysis. Today a number of companies are active in the manufacture and development of electrolysis technologies with Proton, Hydrogenics, Giner, and ITM Power being leaders in the field. figure (5.3) shows the largest electrolyzer in the world. Norck Hydro Norsk 135MW.



Source: Nel 2018c, slide 4. © Nel.

**Fig. (5.2) World's Largest Electrolyzer: Norsk Hydro 135 MW Electrolyzer, Glomfjord,
Norway**

Those electrolyzers were often used in conjunction with large hydropower resources and reached significant sizes, notably Nel's (Norsk Hydro) world record 135 MW electrolyzer in Glomfjord (Norway), which was built in 1953 and operated until 1991 (Nel 2018c) (figure).

5.2 General characteristics of Electrolyzers:

The electrolysis cell is the basic element of the electrolytic hydrogen production system. An electrolysis module is constituted by individual electrolysis cells connected in either series or parallel as shown in Figure (5.1). The V_{cell} and I_{cell} represent the voltage and current of the single electrolysis cells whereas V_M and I_M correspond to the voltage and current of the electrolysis module. When the cells within the module are connected in parallel, every individual cell is connected to the respective power supply terminals, since in this case each electrode has a single polarity, it is known as unipolar or mono polar. If the cells within the electrolysis module are connected in series the same current flows through all the cells, in this case the negative electrode of one cell is connected to the positive electrode of the next cell and is also called bipolar. An electrolysis module is most commonly also referred to as a cell stack [65]

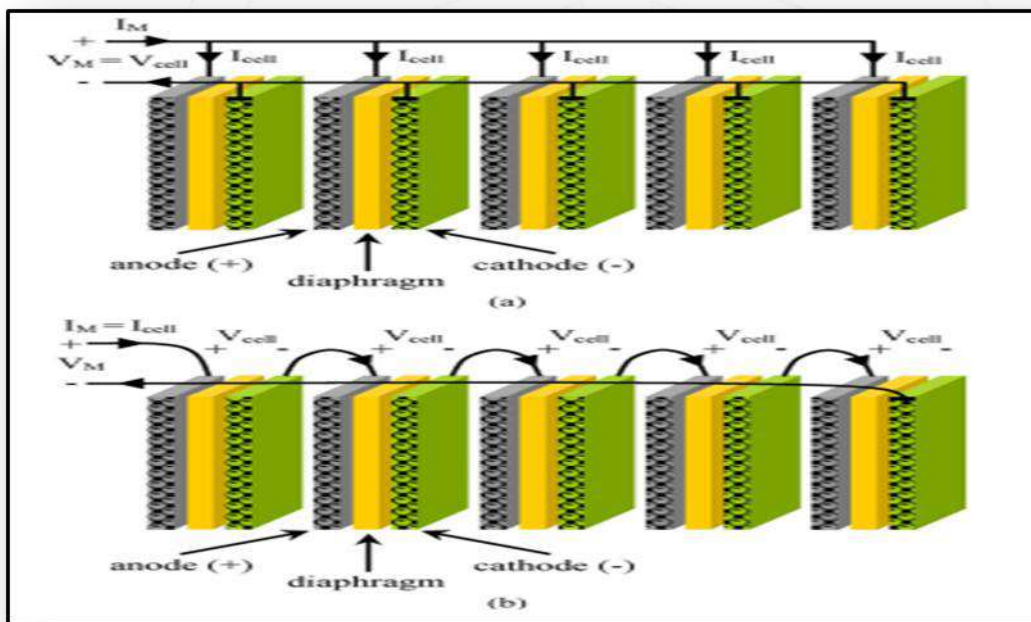


Figure (5.3): Configuration of an electrolysis module: (a) unipolar module or parallel connection of cells; (b) bipolar module or series connection of cells [44].

[44]. Ursu'a, BHydrogen production with alkaline electrolyzers: Electrochemical modelling, electric power supplies and integration with renewable energies, (in Spanish) Ph.D. dissertation, Dept. Electr.

From Figure (5.1) it is clear that in a mono polar module $VM = V_{cell}$ and in a bipolar module $IM = I_{cell}$. Electrolyzers with mono polar cell stacks are called tank or mono polar electrolyzers and electrolyzers with bipolar cells stacks are called filter press or bipolar electrolyzers ^[66]. Each electrolyzer has its own benefits and drawbacks. Mono polar electrolyzers function on a low voltage but high current power supply, they are simple and sturdy and can be easily aintained. Bipolar electrolyzers on the other hand function on a high voltage low current power supply, can achieve high current densities within each cell and are compact in design. Most electrolyzer manufacturers prefer the bipolar stack design as they are believed to be more suitable for hydrogen production ^[73]. In general, an electrolysis plant includes other auxiliary equipment such as drying units, compression units and cooling systems. The oxygen produced is vented directly into the atmosphere and in some cases, hydrogen is produced at high pressures there by reducing the need for a compression unit. Overall electrolyzers are reliable and stable devices that do not require constant maintenance since they do not have too many moving parts. They are also quiet and modular and can be used in a wide range of applications. Even though electrolyzers are a well-known technology their combination with renewables to produce green hydrogen and contribute to the electric grid operation requires further improvements in the reduction of manufacturing costs, operation under various electricity supply profiles and better efficiencies.

In this respect, there is still a long way to go in many aspects such as: / reduction of manufacturing, distribution, and installation costs; / efficiency improvement: electrolysis module, power supply, peripherals, control system, etc.; / operation under variable electric supply profiles; / increase of the operating temperature and pressure.

5.3 Fundamentals of Electrolysis:

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5.3.1 Redox Reaction:

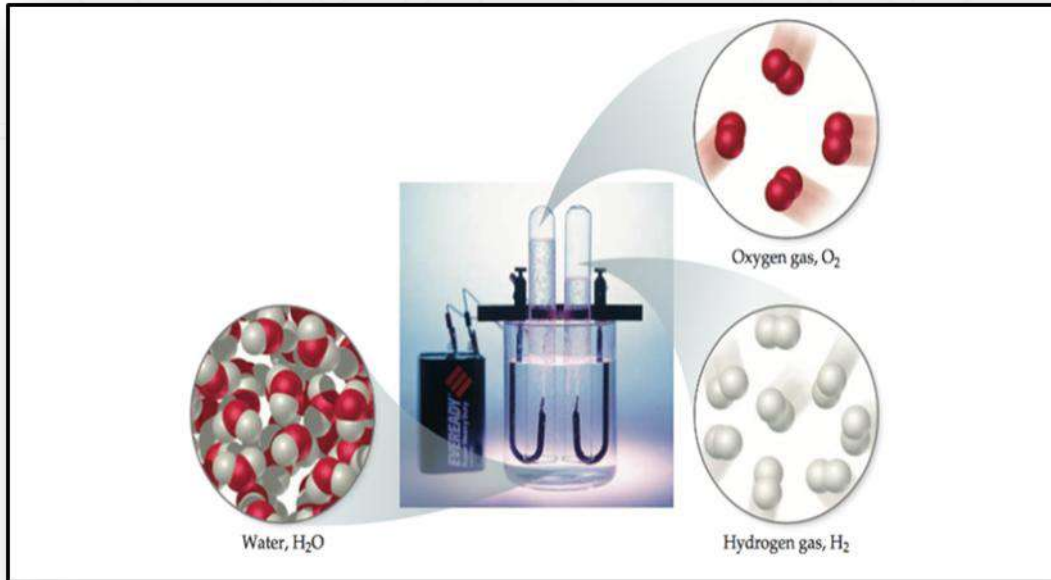


Figure (5.4). Electrolysis of water. Water decomposes into its component elements, hydrogen and oxygen, when an electrical current is passed through it. The volume of hydrogen, collected in the right test tube, is twice the volume of oxygen^[185].

Electrolysis is a promising option for carbon-free hydrogen production from renewable resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer.

Electrolysis is the electrochemical process to split water into hydrogen and oxygen. This process involves a reduction-oxidation reaction. In general, an electrolyzer is composed of an anode (positive electrode), a cathode (negative electrode) and an electrolyte. For starting the electrolysis, a voltage must be applied between the two electrodes. Under applied voltage, the positively charged ions migrate to the negative electrode, where these gain electrons and are reduced. Conversely, negatively charged ions move to the positive electrode losing electrons and oxidizing. As a result, hydrogen is generated in the cathode and oxygen in the anode. The governing reaction of electrolysis is expressed by Eq. (5.1).

Figure 5.1 illustrates a simple setup of the water electrolysis



Based on the type of electrolyte, there are three main types of electrolyzers: (1) alkaline, (2) proton exchange membrane (PEM), and (3) solid oxide. Depending on the nature of the electrolyzer (acid or basic), the anode and cathode experience different reactions. Table 5.1 summarizes the electrochemical reactions occurring in the three types of electrolysis. Figure 5.2 shows a schematic representation of the three electrolyzer configurations and the direction of the reactions. A short, comparison between alkaline, Solid oxides and PEM is shown in table (5.1).

5.4 Electrolyzer Technologies:

Electrolysis of water is one such most capable method for production of hydrogen because uses renewable H_2O and produced only pure oxygen as by-product. Additionally, in electrolysis process utilizes the DC power from sustainable energy resources for example solar, wind and biomass. Electrolyzer technologies have been gaining momentum as the interest around hydrogen production increases. Alkaline, proton exchange membrane (PEM) and solid oxide electrolyzers are commercially available and are at a good technology readiness level ^[67].

Figure (5.5) shows a schematic representation of the three electrolyzer configurations and the direction of the reactions. A short Comparison of technologies In order to understand better the differences among the three technologies, Table (5.1) is built to visualize the most impactful characteristics that could help in the selection decision of each specific system.

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Table (5.1): Anode and Cathode reactions for three types of electrolyzers

	Alkaline	PEM	Solid Oxide
Anode	$4OH^- \rightarrow 2H_2O + 4e^- + O_2$	$2H_2O \rightarrow 4H^+ + 4e^- + O_2$	$2O^{2-} \rightarrow 4e^- + O_2$
Cathode	$4H_2O + 4e^- \rightarrow 4OH^- + 2H_2$	$4H^+ + 4e^- \rightarrow 2H_2$	$2H_2O + 4e^- \rightarrow 2O^{2-} + 2H_2$

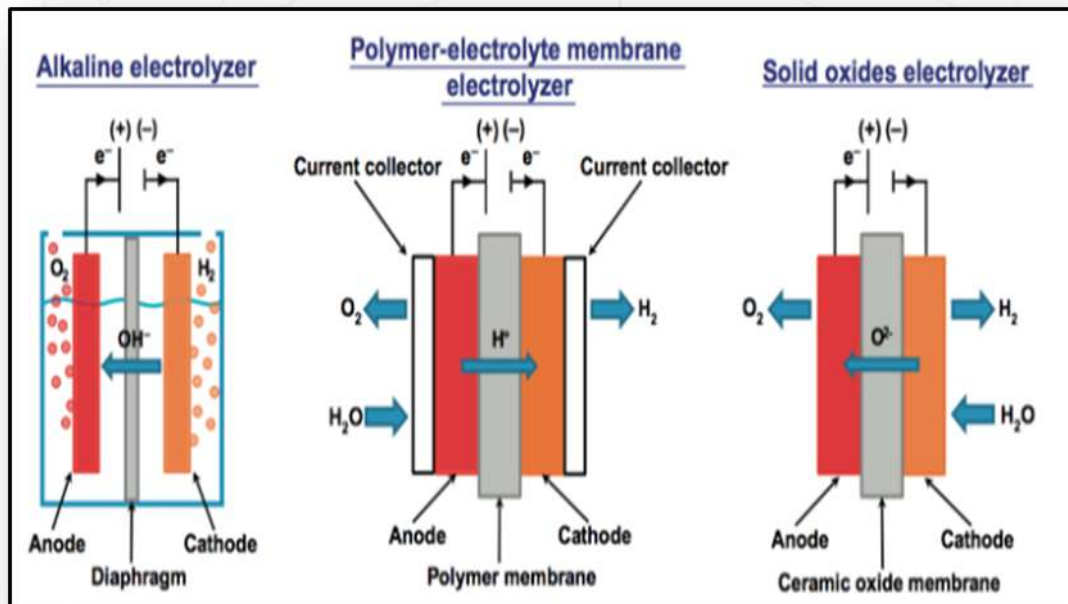


Fig.(5.5): Schematic representation of different water electrolysis for water splitting.

Understanding the nature of reactions and the technology of the electrolyzer is important to select the most suitable method. Temperature and pressure are two important parameters to keep in mind when choosing the electrolyzer. Also, size lifetime and price are important parameters when selecting the electrolyzer technology.

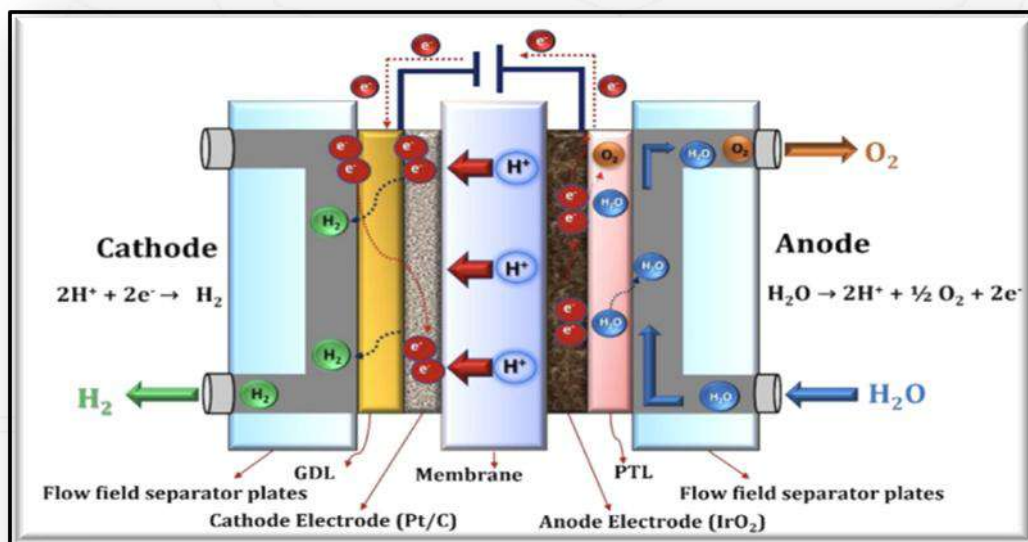
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5.5 Proton exchange membrane electrolysis:

The defining feature of a proton exchange membrane (PEM) electrolyzer is the proton conducting membrane electrolyte. The most widely accepted membrane material is Nafion produced by (DuPont de Nemours Co). The modules of the PEM electrolyzer are arranged in a bipolar configuration constructed with bipolar plates that not only serve the purpose of electrical connection but also to evacuate the product gases. The bipolar plates are made of electrically conductive materials. To achieve the necessary amount of hydrogen production by the electrolyzer, several electrolysis cells comprising the membrane electrode assembly (MEA) are placed between the bipolar plates. The cell components such as the anode, cathode and membrane set form the MEA ^[68]. The electrodes are usually doped with electrocatalysts of noble metals like platinum on the cathode side and iridium on the anode side ^[69]. platinum at the cathode for proton reduction and iridium oxide at the anode for water oxidation.

PEM water electrolyzers can produce high-purity hydrogen at lower temperature ranges of 70–90 °C. IrO₂ and Pt are used as the anode and cathode catalyst materials, respectively ^[70,71]. Nafion membrane is typically used to conduct the hydrogen ions (H⁺); it is applied as a solid electrolyte, as opposed to the liquid electrolyte in alkaline electrolyzers. A PEM electrolyzer cell schematic diagram and reaction mechanism are shown in Figure (5.6).



Fig(5.6): Electrolysis of water. Water decomposes into its component elements, hydrogen and oxygen, when an electrical current is passed through it.

Hydrogen ions migrate through the solid membrane to form hydrogen molecules. Because of the electrolyte's acidic nature and the electrode's metallic surfaces, the reaction kinetics of PEM electrolyzers are rapidly induced compared with those of an alkaline cell ^[72]. As a result, PEM electrolyzers are safer and can operate at atmospheric pressure on the anode side while the cathode side is exposed to higher pressures ^[72, 73].

Between the flow fields of the bipolar plates and the MEA a conductive layer is added. This layer is known as the gas diffusion layer (GDL) and is added to improve the electrical connection between the bipolar plates and the MEA and also to insure the effective mass transport of both the reactant water and the product gases. The cathodic GDL is often made of carbon paper. This material is not suitable for use at the anode as the highly oxidative conditions at this electrode would quickly decompose the carbon paper. Instead, a titanium or similar inert metal mesh is inserted between the flow fields and the MEA .

A significant challenge of PEM electrolyzers is their difficulty in scaling up for large-scale (MW) applications. Therefore, an extensive analysis should be performed to validate the large-scale unit's characteristics and the expected lifetime of PEM electrolyzers.

The use of PEM has increased in recent years because it works at high current density, which may reduce operating costs, especially when dynamic sources such as wind or solar energy are used. It requires less space and large-scale facilities will have a significantly smaller footprint than with AE. With PEM, it is also easier to compress the hydrogen, which may reduce transport and storage costs. While PEM is a younger and more expensive technology, some studies suggest the long-term (5-10 year) efficiency is slightly higher. The cost is expected to drop rapidly in the next 5-10 year and the long-term cost is already more or less the same as for AE (Blue Move, 2018). Proton exchange membrane (PEM) electrolysis is the electrolysis of water in a cell equipped with a solid polymer electrolyte.

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5.6 PEM electrolysis Components:

PEM electrolysis stack (most common) materials :

- Membrane Electrode Assembly (MEA).
- Membrane.
- Anode and Cathode electrode with electrocatalyst..
- Gas diffusion Layer (Current collector).
- Bipolar plates:

Anode: Titanium+(platinnm coatingd coating).

Catode: Titanium+(Gol coating).

Figure (5.6) shows the fundamental principle for electrolysis cell. The general principle for all three technologies is the same. When a high voltage is applied to an electrochemical cell in presence of water, hydrogen and oxygen gas bubbles evolve at cathode (negative electrode) and anode (positive electrode) respectively.

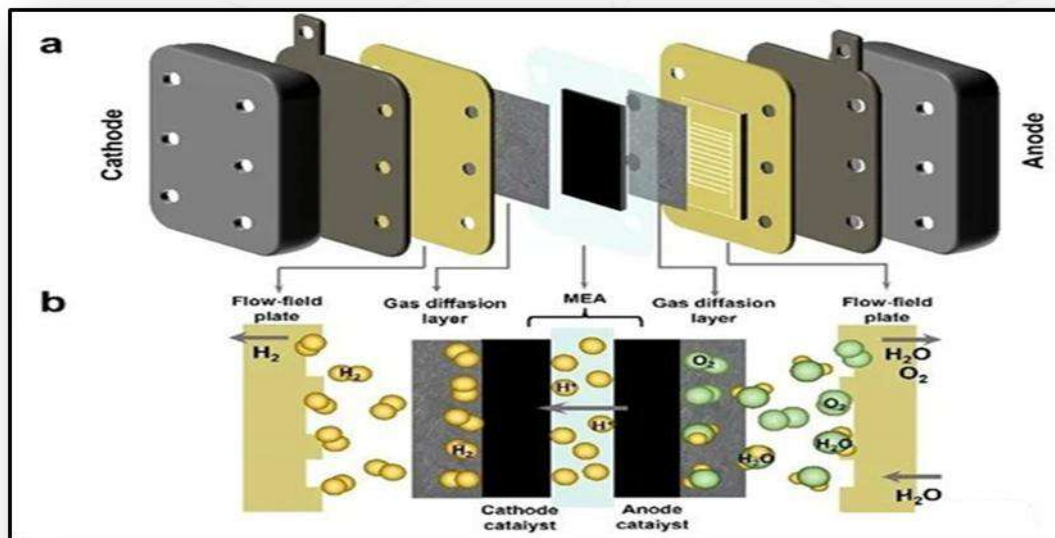


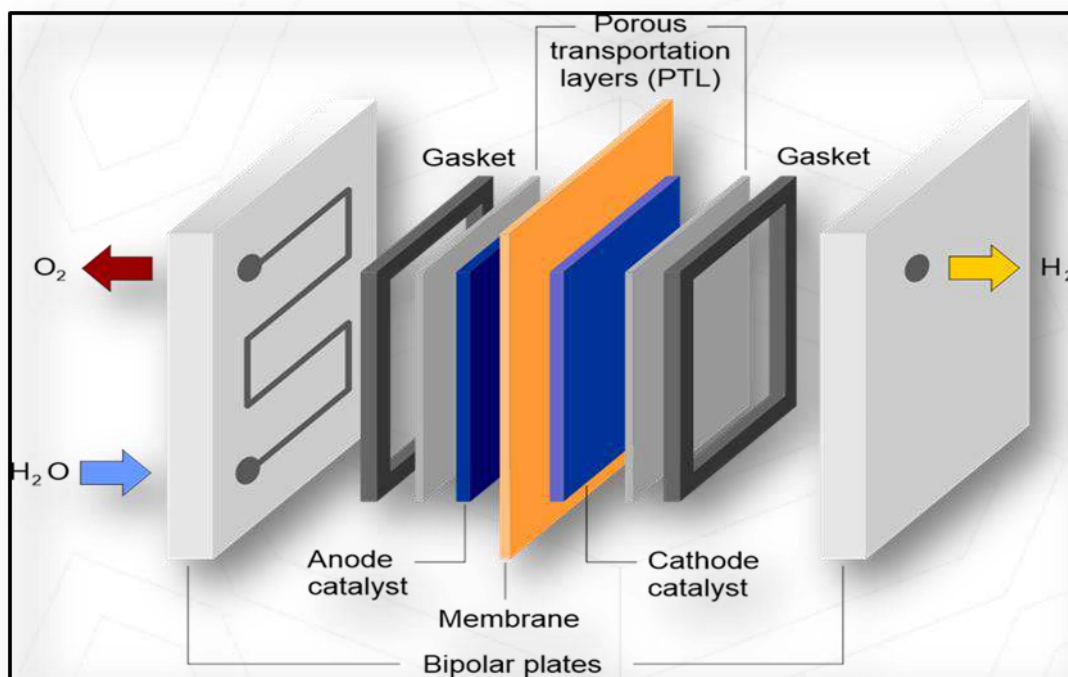
Fig. (5.7). The fundamental design of a PEM electrolysis cell.

The fundamental design of a PEM electrolysis cell, as shown in Figures (5.6),(5.7) below, the two half-cells are separated by the membrane. The components of PEM are membrane electrode assembly (includes membrane, anode and cathode electrodes), gas diffuser (current collector), gasket, bipolar plates and interconnector.

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The core component of PEM cell is membrane electrode assembly (MEA) in which electrodes is coated directly. Gas diffuser (current collector) and gasket are used to enable an electric current to flow between the bipolar plates and the electrodes. The bipolar plates are electrically conductive, support to transport liquid water at the anode and oxygen and hydrogen out of the electrolysis cell. Materials such as titanium and coated stainless steel have to be used for constructing the bipolar plate, current collector, and, if necessary, the support for catalysts.



(5.8) The main component of single cell in a PEM electrolyzer

5.7 Electrochemical process:

Water electrolysis is an electrochemical process in which the hydrogen is produced by splitting water using an electrical current passed through two electrodes. The electrolysis of water is not cost-effective unless the electricity comes from a renewable sources like solar energy and wind energy. the following mechanism as shown in Fig. (5.11) chemical reactions at the anode and the cathode:

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- Water reacts at the anode to form oxygen and positively charged hydrogen ions (protons).
- The electrons flow through an external circuit and the hydrogen ions selectively moves across the PEM to the cathode.

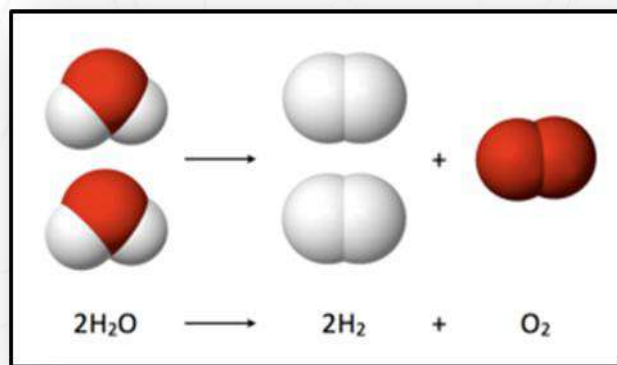


Fig (5.9). Pictured molecular formula of conversion of water to hydrogen and oxygen

- At the cathode, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.
- Anode Reaction: $2\text{H}_2\text{O} \rightarrow \text{O}_2 + 4\text{H}^+ + 4\text{e}^-$
- Cathode Reaction: $4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2$

he general electrolysis reaction:



(SPE)^[92] Solid Polymer Electrolyte (SPE)water. that is responsible for the conduction of protons, separation of product gases, and electrical insulation of the electrodes. The PEM electrolyzer was introduced to overcome the issues of partial load, low current density, and low pressure operation currently plaguing the alkaline electrolyzer .^{[74][75]} It involves a proton-exchange membrane.

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Electrolysis of water is an important technology for the production of hydrogen to be used as an energy carrier. With fast dynamic response times, large operational ranges, and high efficiencies, water electrolysis is a promising technology for energy storage coupled with renewable energy sources. In terms of sustainability and environmental impact, PEM electrolysis is considered as a promising technique for high purity and efficient hydrogen production since it emits only oxygen as a by-product without any carbon emissions. The IEA said in 2022 that more effort was needed.^[76] PEM electrolysis cells typically operate below 100 C° (212 F°).^[77] These cells have the advantage of being comparatively simple and can be designed to accept widely varying voltage inputs, which makes them ideal for use with renewable sources of energy such as photovoltaic solar panels. AECs optimally operate at high concentrations of electrolyte (KOH) or potassium carbonate and at high temperatures, often near 200 C° (392 F°).



FIG (5.10) A PEM electrolyser unit container.

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5.8 PEM electrolysis System Components:

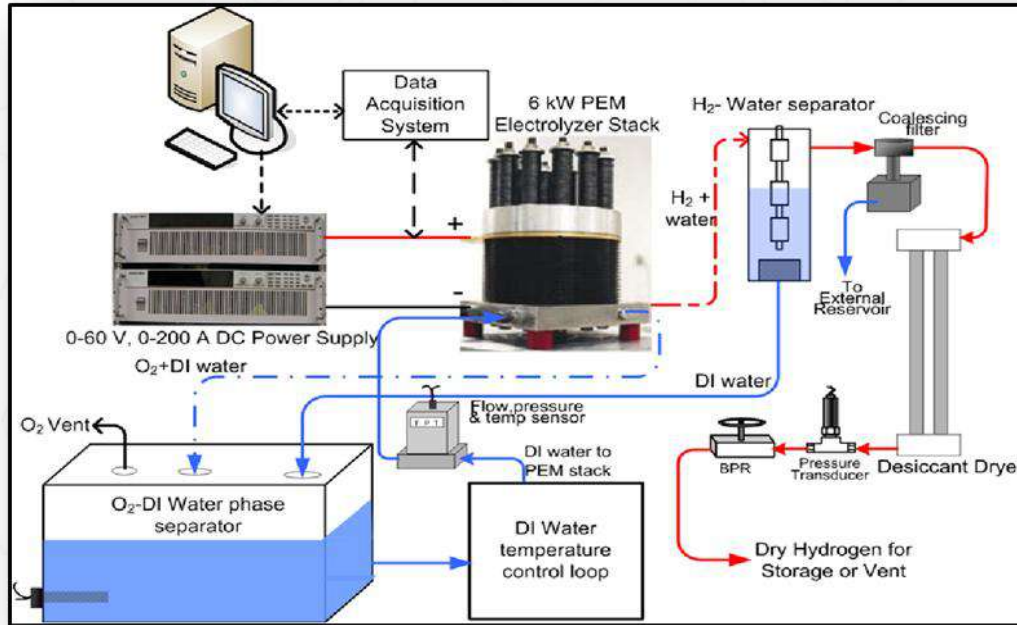


Fig.(5.11). PEM electrolysis System Components.

5.9 Operation:

The DI water loop maintains the temperature and resistivity of water using the chiller and carbon mixed bed filters respectively. The oxygen phase separator is equipped with level sensing float, temperature, resistivity and combustible gas detector sensors to monitor system performance and safety. After achieving desired resistivity and temperature of DI water, the stack is supplied with power using two DC power supplies and DI water run through the stack. Before entering the stack, DI water goes through 10µm filter and sensing stage where its temperature, flow, pressure and resistivity are monitored again for stable and safe operation. Hydrogen gas coming out of the cathode side is separated from liquid water in high pressure hydrogen-water separator. A coalescing filter, immediately following the separator, removes most of the remaining liquid water from hydrogen gas. An automatic drain connected to the coalescing filter collects and recycles the DI water back to external reservoir with the help of hydrogen system pressure.

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A two-tube desiccant drying system performs the remaining drying process of the hydrogen gas. Dry hydrogen product gas then enters the sensing stage equipped with mass flow, temperature, pressure and dew point sensors. A back pressure regulator can be adjusted to maintain the hydrogen system pressure. Oxygen from anode side is separated from DI water in oxygen phase separator where oxygen is then vented out using a check valve and DI water is reused.

❖ Deionized water, or DI water, is water that has had all (or most) ions removed.



Fig. (5.12) Application of electrolyzer using seawater

5.10 (PEM) Advantages:

One of the largest advantages to PEM electrolysis is its ability to operate at high current densities^[95] This can result in reduced operational costs, especially for systems coupled with very dynamic energy sources such as wind and solar, where sudden spikes in energy input would otherwise result in un captured energy.

The polymer electrolyte allows the PEM electrolyzer to operate with a very thin membrane (~100-200 μm) while still allowing high pressures, resulting in low ohmic losses, primarily caused by the conduction of protons across the membrane and a compressed hydrogen output^[78] The polymer electrolyte membrane, due to its solid structure^[79], exhibits a low gas crossover rate resulting in very high product gas purity. Maintaining a high gas purity is important for storage safety and for the direct usage in a fuel cell. The safety limits for H_2 in O_2 are at standard conditions 4 mol -% H_2 in O_2 .^[80] Another important advantage is that the PEM. Electrolyzer operates at low temperature which significantly reduces the startup time and allows for the instantaneous production of hydrogen making the PEM electrolyzer quite adaptive to the intermittent nature of renewables. It also operates at high pressure thus the produced hydrogen gas is also at a higher pressure eliminating the need for an external compression unit. The electrolyte concentration is detached from the operating conditions and does not deteriorate over prolonged usage thereby enabling the electrolyzer to operate for many hours without requiring maintenance. On the downside since the membrane is highly acidic and the electrolyzer is operated at low temperature noble metals such as platinum or iridium are used as electrocatalysts making the PEM electrolyzer technology expensive. Additionally, the conductivity of the membrane highly depends on humidity. At high temperatures the membrane could dry out and lose its conductivity.

5.11 PEM efficiency:

When determining the electrical efficiency of PEM electrolysis, the HHV can be used.^[98] This is because the catalyst layer interacts with water as steam. As the process operates at 80 $^\circ\text{C}$ for PEM electrolyzers the waste heat can be redirected through the system to create the steam, resulting in a higher overall electrical efficiency.

PEM electrolysis has an electrical efficiency of about 80% in working application, in terms of hydrogen produced per unit of electricity used to drive the reaction^[81,82] The efficiency of PEM electrolysis is expected to reach 82-86%^[18] before 2030, while also maintaining durability as progress in this area continues at a pace^[83] The efficiency of a water electrolyzer is equal to the ratio between the energy content in the produced hydrogen and the electrical energy supplied to the process.

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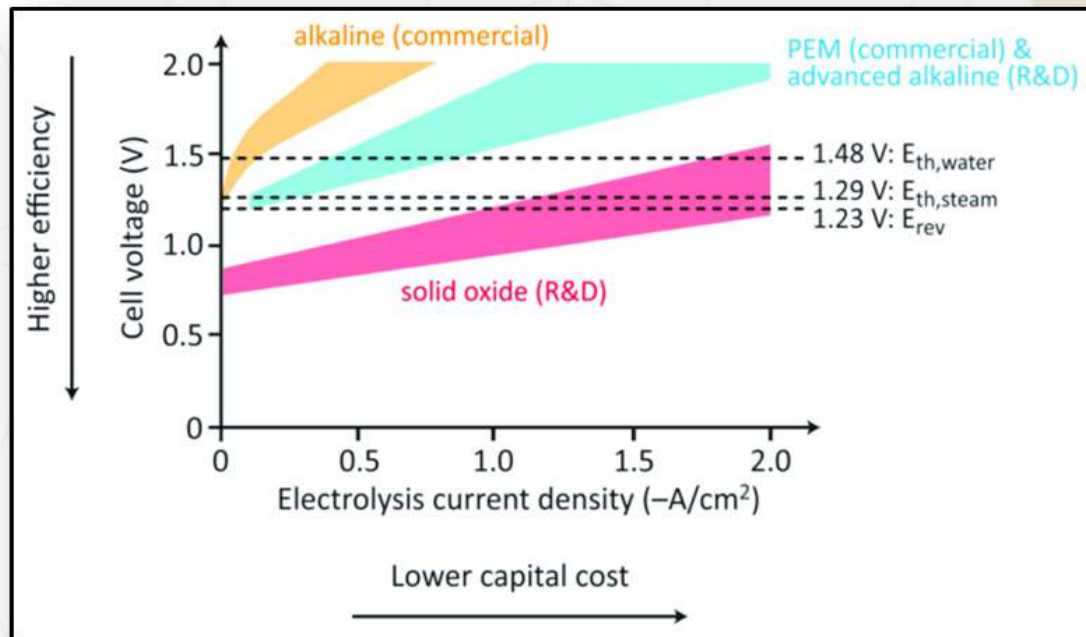


Fig.(5.13). Comparison between alkaline, polymer electrolyzer membrane (PEM), and solid oxide electrolyzers in terms of voltage vs. current density^[102].

APEM electrolyzer's efficiency is inversely related to the cell potential, which is determined by the current density, which is directly proportional to the rate of hydrogen production per unit of electrode active area. More hydrogen would be produced with a greater current density, but at a lower efficiency. Typically, cell voltage is set at around 2 V, however if efficiency is more essential than size (and capital cost) a lower nominal voltage (as low as 1.6V) can be used. Another cause of inefficiency is the hydrogen permeation through the polymer membrane. At low working pressures, this is usually inconsequential, but at very high pressures (>100 bar), it can have a considerable impact on total efficiency. Additionally, there are power losses in voltage regulation, and the auxiliary equipment also requires some power (pumps, fans, solenoid valves, instrumentation and controls^[83]).

5.12 Electrolyzer Performance Degradation with Time:

When sizing an electrolyzer for use with PV plants, one must account for voltage increases over time. If efficiency or hydrogen generation rate are crucial, end-of-life electrolyzer performance should be considered rather than beginning of life electrolyzer performance.

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The voltage rises faster in the first few thousand hours of operation, but eventually levels out ^[84].

The accumulation of water content in the membrane, as well as oxidation of the catalyst and other metallic components, are the causes of the voltage increase. This performance deterioration could be avoided with appropriate design and judicious material selection ^[80].

5.13 Electrochemistry and Thermodynamics:

From the electrochemical perspective, the energy required for water splitting can be obtained from the standard potentials, for the two half reactions. The standard potential measures the ability of an element to start reducing at 1 atm and 298 K.

Table 5.2: Comparison of water electrolysis methods ^[107]

Parameter	Alkaline electrolyzer	PEM electrolyzer
Cell temperature (°C)	60 - 80	50 - 80
Cell pressure (105 Pa) (bar)	<30	<30
Current density (mA cm ⁻²)	0.2 - 0.4	0.6 - 2.0
Cell voltage V	1.8-2.4	1.8-2.2
Power density (mW cm ⁻²)	< 1	< 4.4
Efficiency (HHV) (%)	62 - 82	67 - 82
Specific energy consumption stack (kW h) (Nm ³)	4.2 - 5.9	4.2 - 5.6
Partial load range (%)	20 - 40	5 - 10
H ₂ production rate (Nm ³ h ⁻¹)	< 760	< 10
Lifetime stack (h)	< 90 000	< 20 000
Degradation rate (mV h ⁻¹)	< 3	< 14

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Thermoeconomic Assessments of Green Hydrogen in Libya Using Solar Photovoltaics (PV) Panels and PV&PEM Electrolyzer.

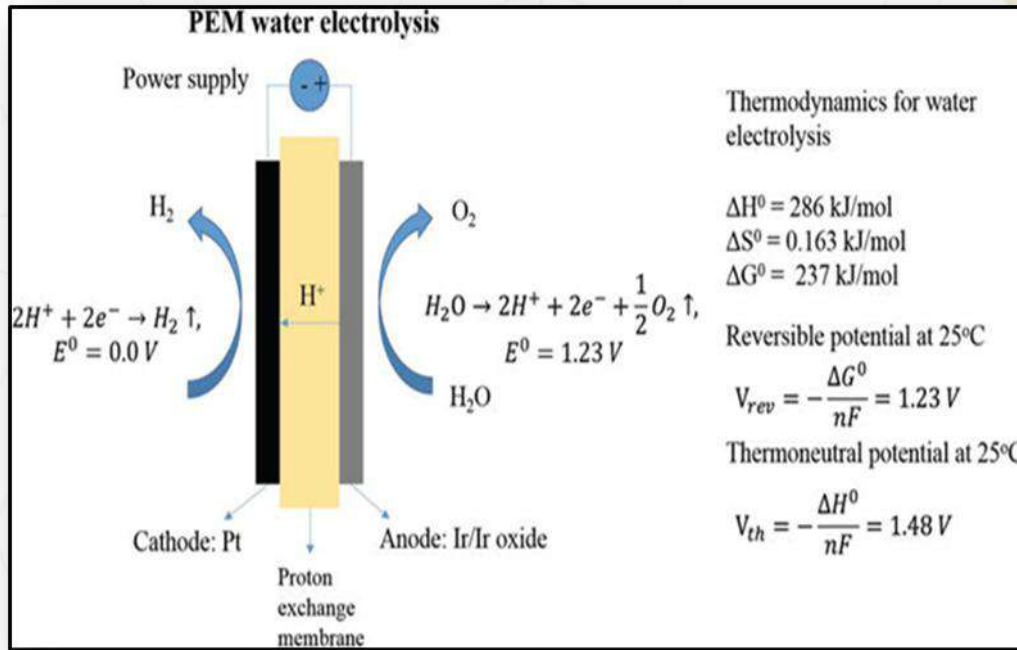
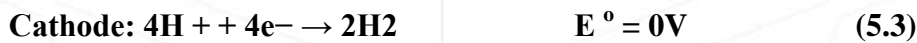
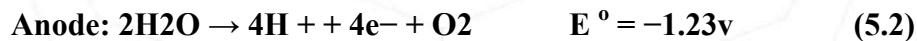


Fig. (5.14). Schematic diagram of PEM water electrolysis and the fundamental thermodynamic properties.

For a PEM electrolyzer, the reactions and standard potentials for the anode and cathode are given by expressions (5.2) and (5.3).



Then, the standard cell potential (E^0) for the complete reaction of water electrolysis is given by the equation. (5.4)

$$E^0 = E^0_{\text{cathode}} - E^0_{\text{anode}} = 1.23 \text{ V} \quad (5.4)$$

At standard conditions, water splits into hydrogen and oxygen when a voltage of at least 1.23 V is applied to the electrodes. This potential is the reversible voltage required to split water electrolytically [85]. This means that all the energy supplied to the reaction will be maximized to only split water with zero heat losses. The second law of thermodynamics tell us that this will never occur. The reversible voltage is related to the Gibbs free by the Equation. (5.5).

$$E^0 = \Delta G^0 / nF \quad (5.5)$$

where, $n = 2$, is the number of electrons involve in the reaction, and $F = 96485 \text{ C/mol}$, is the Faraday's constant.

Substituting values in equation (5.5) results in a Gibbs free energy value of $\Delta G^0 = 237.22 \text{ kJ/mol}$.^[86] From the thermodynamic perspective, the energy needed to split water can be determined by the changing enthalpy (ΔH^0). This energy involves the internal energy of the system (ΔG^0), and the amount of energy transferred as heat (ΔS^0). The thermodynamic relationship is expressed by Eq. (5.6).

$$\Delta H^0 = \underbrace{\Delta G^0}_{\text{electricity}} + T \underbrace{\Delta S^0}_{\text{heat}} \quad (5.6)$$

By application of equation (5.6), the Gibbs free energy $\Delta G^0 = 237.22 \text{ kJ/mol}$, and the ideal entropy ($\Delta S^0 = 0.163 \text{ kJ mol}^{-1} \text{ K}^{-1}$) of gaseous water at standard conditions (298 K and 1 atm)^[86], the standard enthalpy change of formation of liquid water results in a value of $\Delta H^0 = 285.8 \text{ kJ/mol}$.

The electrical potential related to enthalpy energy change is commonly called thermo neutral voltage (V^0_{tn})^[87]. Using ΔH^0 in equation (5.6), the thermo neutral voltage to split water, at standard conditions, is $V_{tn} = 1.48 \text{ V}$.

This value represents the global energy required for the reaction to occur. An electrolyzer with operating voltage equals to 1.48 V would be 100% efficient. In reality, a further potential needs to be applied to accelerate the reaction to a practical rate.

Summarizing, the thermo neutral (V^0_{tn}) and reversible (E^0) voltages establish the conditions for the electrolysis process. When the applied voltage is lower than the reversible voltage ($V_{cell} < E^0$), the reaction does not occur. If the applied voltage is between V^0_{tn} and V_{rev} , extra heat is required to operate the reaction. And when the applied voltage is bigger than the thermo neutral voltage ($V_{cell} > V^0_{tn}$) the reaction occurs and produces heat^[87].

Figures[5.7and5.8] illustrate the temperature dependence of the energy and voltages involved during water electrolysis. The increase in thermal energy during water electrolysis is compensated by the decrease in electrical energy in the process.

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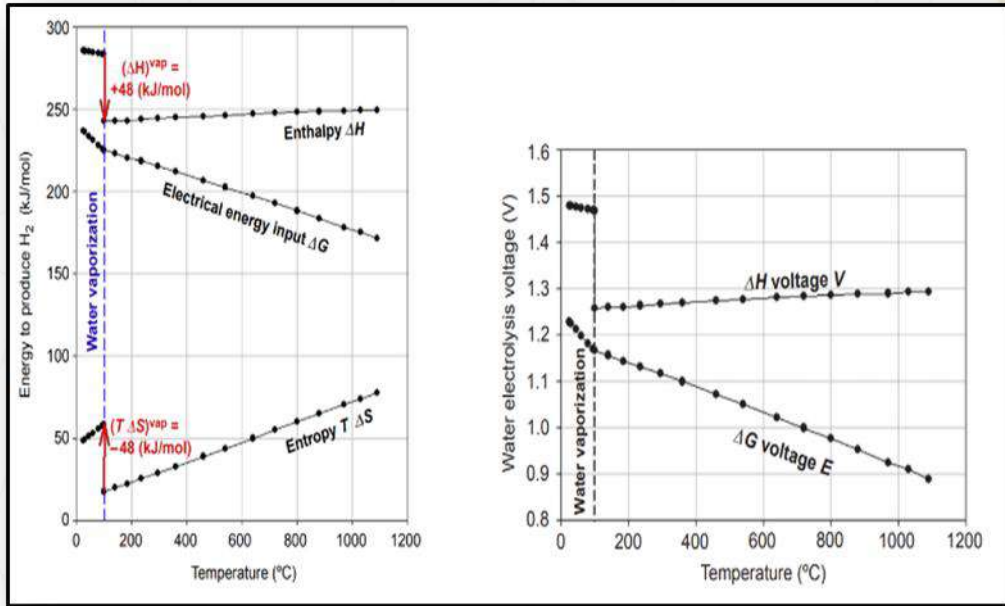


Figure (5.15). Temperature dependence of main thermodynamic parameters for water electrolysis at 1atm.^[86]

Figure (5.16). Thermodynamic and enthalpy water splitting voltages as a function of operating temperature at 1atm.^[108]

5.13.1 Nerst Equation:

All the thermodynamic values in equation (5.15) are temperature and pressure dependent. For conditions different than 1 bar and 298 K, the voltage to start the reaction significantly changes. The effect of pressure and temperature in the reversible potential can be evaluated by using the Nerst equation^[88], expressed by Eq. (5.16)

$$V_{tn} = E^0 + \frac{RT}{2F} \ln \left(\frac{[P_{H_2}][P_{O_2}]^{1/2}}{[P_{H_2O}]} \right) \quad (5.7)$$

where, T is the temperature in kelvin (K), $R=8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$, is the universal gas constant, and p_x are the partial pressure of each of the species.

5.13.2 Kinetics Aspects:

Practically speaking, to produce hydrogen from water a voltage Significantly higher than the reversible potential is needed. As current density increases the cell losses due to membrane, electrode, and interfacial resistances become more important and are known as over potentials (ΔV)^[110]. This, results in a overall cell potential (V_{cell}) equal to the standard potential (E^0),

plus the overvoltage (ΔV). The overvoltage has three main components: (1) activation, (2) concentration, and (3) *ohmic*, as presented in Eq. (5.8)

$$V_{cell} = V^0 + \Delta V_{act} + \Delta V_{con} + \Delta V_{ohm} \quad (5.8)$$

Ohmic Over potential:

The *ohmic* over potential (ΔV_{ohm}) is mainly caused by electrical resistance in the conductors, the electrodes and across the proton exchange membrane. The membrane causes a resistance to the hydrogen ions passing through it. This resistance is related to the humidification, thickness and temperature of the membrane ^[109] energy loss regarding to *ohmic* voltage is transformed into heat during the electrolysis process, which most of it is carried out by the reactant water. The relation between voltage and current is relatively linear, defined by Ohm's law as $V_{ohm} = I_e \cdot R_{ohm}$, where, I_e , is the electrolyzer current; and R_{ohm} is the equivalent resistant in the electrolyzer.

Activation Over potential:

The activation over potential is a measure of the activity in the electrodes ^[108]. The activation over potential (ΔV_{act}) is caused by the reaction interface between anode/membrane and cathode/membrane. Both anode (η_a) and cathode (η_c). over potentials, represent irreversible losses and become dominant at lower current densities in a PEM electrolyzer ^[86]. The activation over potential in a PEM electrolyzer is much smaller in the anode than in the cathode ^[87]. Equations (2.12) and (2.13) are empirical expressions developed to determine the activation over potential in function of the current density for both anode and cathode ^[87].

$$\eta_a = \frac{RT}{\alpha_a z F} \ln \left(\frac{i}{i_{a,o}} \right) \quad (5.11)$$

$$\eta_c = \frac{RT}{\alpha_c z F} \ln \left(\frac{i}{i_{c,o}} \right) \quad (5.12)$$

where, α_x , are the electron transfer coefficients of each electrode, $i_{x,o}$, are the exchange current densities in ($A \text{ cm}^{-2}$) for each electrode and i , is the current density of the stack in ($A \text{ cm}^{-2}$). The electron transfer coefficient is a measure of the symmetry of the activation energy barrier and can range from 0 to 1 ^[110].

Concentration Over potential:

The concentration over potential (ΔV_{con}) is caused due to the mass transport limitations. This transport limitation involves the depletion of charge-carriers at the electrode surface. At lower current this potential can be neglected, however at significantly higher currents when the reactions are at higher rate, the concentration overvoltage becomes relevant. The concentration over potential can be neglected during normal operation conditions, because the gas transport limitations in PEM electrodes are insignificant ^[86].

Understanding the kinetics involved in water electrolysis is important to reduce losses, and make the process more efficient. Furthermore, reducing the over voltages can lead to significant energy savings in the hydrogen production.

The three main over potentials involved during water electrolysis are graphically represented by the I-V characteristic curve of the electrolyzer as shown in Fig. (5.17)

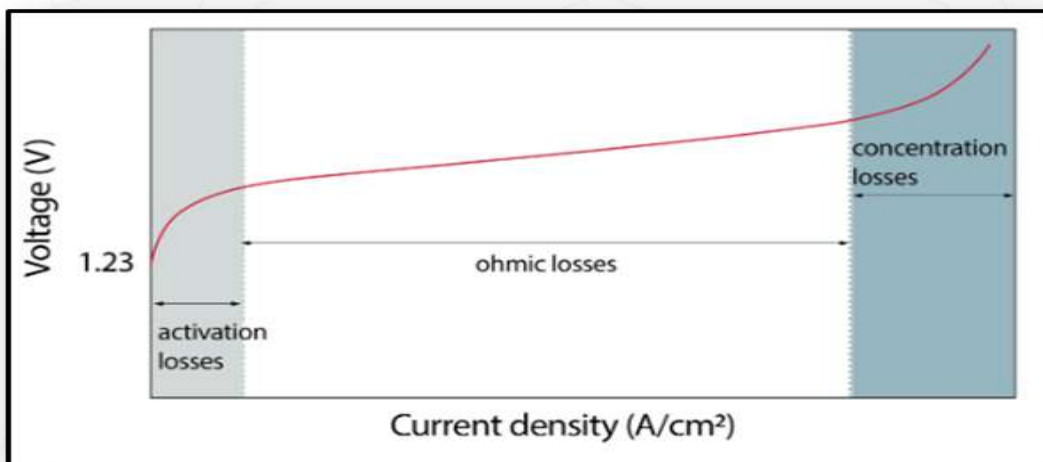


Figure (5.17) Polarization curve depicting three main losses attributed to PEM electrolysis cell operation. (Redrawing by the author ^[86])

Polarization Curve:

The operation of an electrolyzer is characterized by the current density and voltage (I-V) curve or also known as polarization curve. This curve includes information of the potentials and currents involved during the electrolysis process at specific temperature and pressures. For a PEM electrolyzer the characterization is made at 1 atm and 298 K. Three main regions, representing the energy losses, are identified in a polarization curve: (1) activation losses, (2)

ohmic losses and (3) mass transport or concentration losses. Figure 5.8 depicts the losses attributed to a PEM electrolyzer.

Concentration overvoltage (V_{con}). Depletion of the charge carriers at the electrodes. It is mainly due to mass transport limitations. A specific phenomenon in this category is the bubble overvoltage, which reduces the effective area of the electrode when the products of the reaction are more abundant, increasing the current density. Hence, it has a greater presence in high current densities.

5.14 Efficiency

The energy content in a specific amount of hydrogen can be calculated by using the molar higher heating value (HHV=283.6 kJ/mol) ^[89]. This value is the amount of calculated by Eq. (5.13).

$$\eta_{el} = \frac{\dot{n}_{H2} HHV}{P_{in}} \quad (5.13)$$

where, \dot{n}_{H2} is the molar rate of hydrogen produced in (mol/s), $P_{in} = i_e \cdot V_{cell}$ is the total power supplied to the electrolyzer in kilowatts (kW). An alternative version for the electrolyzer efficiency as its voltage function (V_{cell}), is given by Eq. (5.14).

$$\eta_{el} = \frac{1.48}{V_{cell}} \quad (5.14)$$

Hydrogen mass flow rate

The amount of hydrogen produced, by water electrolysis, is directly proportional to the electrical current passing through the electrolyzer. According to the second Faraday's law, the hydrogen mass flow rate (\dot{m}_{H2}) can be determined by Eq. (2.15).

$$\dot{m}_{H2} = \frac{M_{H2} \cdot i_e \cdot n_c}{nF} \eta_F \quad (5.15)$$

where, i_e is the electrical current ampers (A), $M_{H2}=2$ g/mol is the molar mass of hydrogen, n_c is the number of cells in the electrolyzer, $n = 2$ is the number of electrons in the reaction, F is the Faraday's η constant, and η_F is the Faraday's efficiency.

Faraday's Efficiency:

The Faraday's efficiency (η_F) is a parameter to assess the utilization of electrons during the water electrolysis^[89]. It is calculated as the ratio between the experimental and the theoretical volume of produced hydrogen. When all the supplied electrons, during the reaction, are producing only hydrogen and oxygen, $\eta_F = 1$. This occurs when the electrodes are very well resistant to corrosion and behave completely stable during the reactions. Electrodes resistant to corrosion are important in order to produce very pure hydrogen during electrolysis. The Faraday's efficiency can be calculated according to the empirical expression given by Eq. (2.16), where, i_e is the electrolyzer current in (A).

$$\eta_F = 0.965 \exp\left(\frac{0.09}{i_e} - \frac{75.5}{i_e^2}\right) \quad (5.16)$$

5.15 Solar-to-Hydrogen: System Description:

Photovoltaic systems can be coupled with water electrolyzers to produce hydrogen. Hydrogen from solar energy becomes a promising alternative to satisfy the power demand of the future. The system configuration to produce hydrogen from solar energy is relatively simple. It comprises: PV panels, direct current (DC/DC) power converter, electrolyzer stack, water and hydrogen storage. The direct current electricity produced from the solar panels can directly feed into to the electrolyzer and produce hydrogen. However, the voltage applied to the electrolyzer is limited by the output power of the solar panels, and the operation voltage of the electrolysis is limited by the operating characteristic of the electrolyzer. Thus, a DC/DC power converter is needed to adjust the voltage levels. Including a battery into the system configuration allows having an extra energy storage source to the system operation. Water quality requirements differ between electrolyzers. For instance, a PEM electrolyzer includes a deionizer unit before the water is fed into the electrolyzer. For an alkaline electrolyzer, water is mixed with potassium hydroxide (KOH) to increase the pH of water. Once the hydrogen is produced, a storage unit is necessary to store the hydrogen. Also, depending on the size and volume production, a distribution system for the hydrogen is needed. Distribution and storage systems become limiting factors when the hydrogen generation is centralized. Additionally, extra components like water separators, gas purification, gas dryer, pipeline, pumps and compressors are needed for an optimal operation^[90].

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A simple representation of the solar-to-hydrogen system configuration is shown in Fig. (5.18).

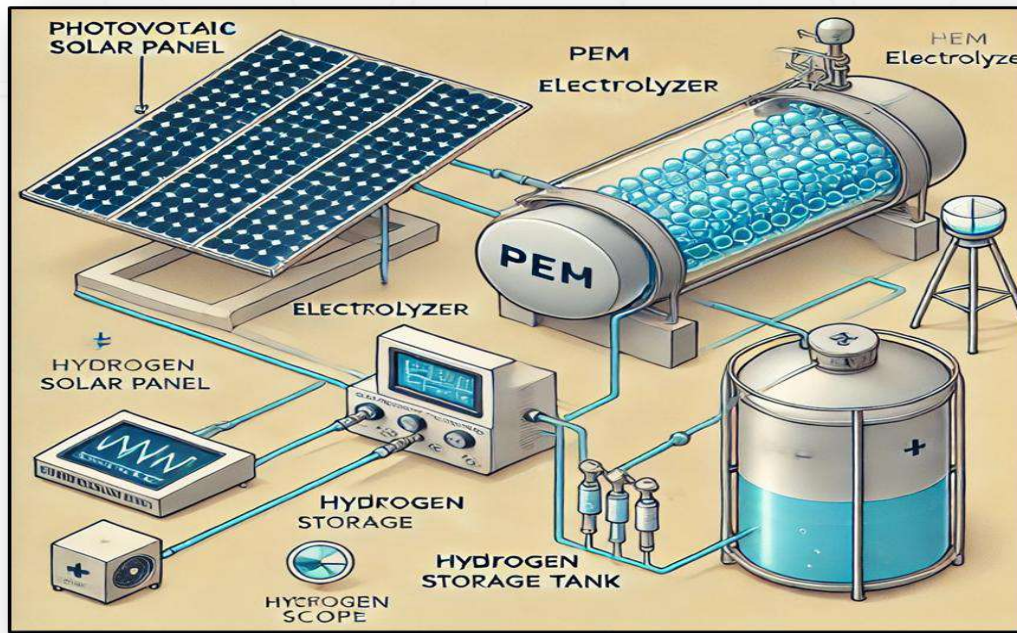


Figure (5.18): Schematic representation of a photovoltaic-electrolyzer hydrogen generation system. (Redrawing by the author).^[89]

Producing hydrogen using PV electricity is a way of storing solar energy and tackle the limitations of its intermittent nature. However, the intermittency of solar energy brings challenges to the operation of the electrolyzer and determines whether the production of hydrogen is economically viable. Power control management, assessment of the system performance, and designing system guidelines are some of the most important concepts needed to investigate, in a solar-to-hydrogen system, to increase the fast integration of renewable energies using hydrogen.

CHAPTER 6

6.1 Introduction:

This chapter presents the simulation of a solar-to-hydrogen (*S2H*) system. Each component in the system is simulated separately, based on a model that describes the physical and chemical principles of the individual component. The model is written in the mathematical tool Matlab Simulink, and structured on three different modules: the photovoltaic module as a primary energy source; the water PEM Electrolyzer as a hydrogen generator; the gas storage tank acting as a sink for the generated hydrogen,

6.2 System Description:

This configuration represents a simple setup in which the photovoltaic (PV) modules serve as the main power source, directly supplying energy to the electrolyzer, which acts as the load. The design features a 1.5 MW PV system directly coupled to a 1.25 MW polymer electrolyte membrane (PEM) electrolyzer. The PV array generates direct current (DC) electricity, which the electrolyzer uses to split water into hydrogen and oxygen. To maintain a steady water supply during operation, a water tank is connected to the electrolyzer via a pump. A general layout of the system is presented in Figure.6.1. The simulation is conducted in the MATLAB/Simulink environment by individually modeling each component. This approach allows for better error control and easier debugging of the simulation blocks. Each system block is carefully implemented and analyzed to ensure sufficient accuracy for the overall simulation, resulting in reliable outcomes. The models for the PV solar system, DC/DC buck converter, electrolyzer, and hydrogen tank are developed and effectively integrated.

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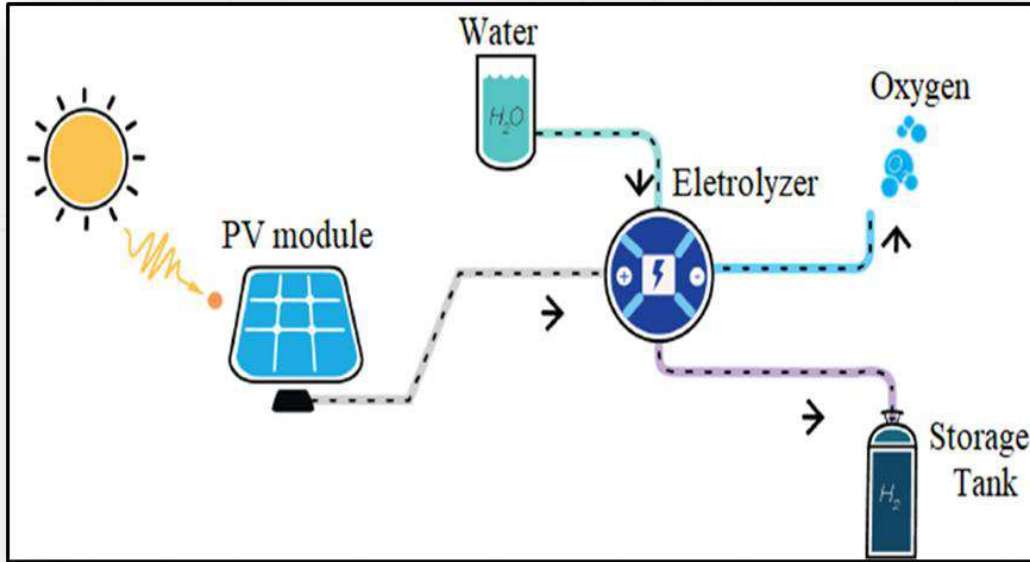


Figure (6.1): General representation of the S2H system layout.

6.3 System Modeling:

A model in Mat lab/Simulink of the PV array, PEM electrolyzer, and storage tank is presented in the following sections.

6.3.1. PV Array Mode:

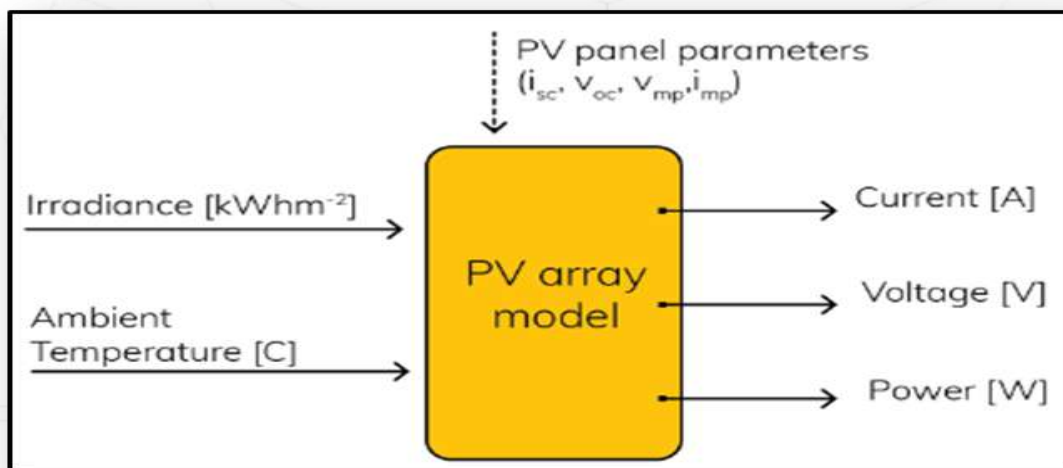


Fig. (6.2) Block diagram of the PV module, representing the inputs and outputs signals of the model.

The PV array model simulates the performance of the solar modules under any irradiation and temperature conditions. The developed model is flexible and allows to simulate different system configurations of the PV system. Therefore, the parameters that affect the system performance can be analyzed and then select the most optimal design. Understanding of how the solar modules operate, under certain weather conditions, and estimate the energy yield of the system, are necessary for optimal system design.

Irradiance, ambient temperature, and the PV panel parameters are taken as input variables for this model. As a result, the model outputs are the current, voltage, and the power of the PV panel. A simplified block representation of the model with the inputs and outputs variables is shown in Fig.6.2.

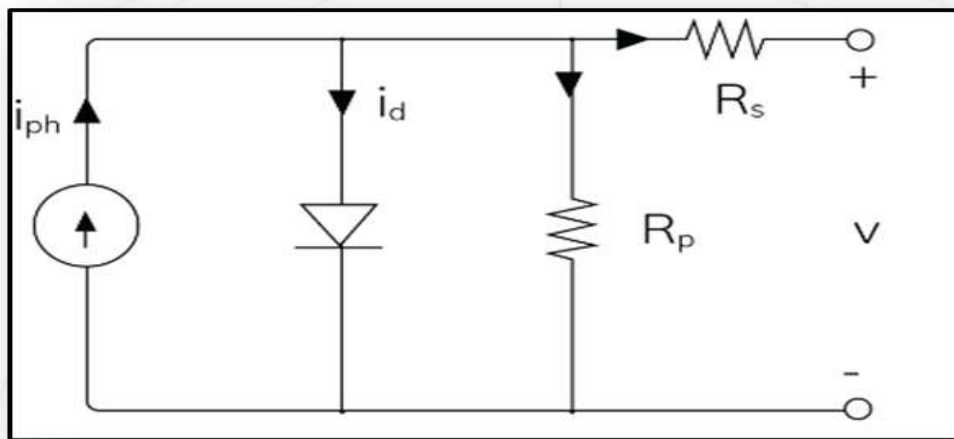


Fig. (6.3): Equivalent electric circuit of a solar cell ^[91]

Using the fundamentals of a solar cell defined in chapter 3, and the simplified equivalent electric circuit of the solar cell, shown in Fig.6.3, it is possible to calculate the voltage and current of the solar cell. The circuit includes a current source as the photocurrent generator, a diode branch, and two resistors. Resistor (R_s) represents the resistance of current through the emitter and in the metal contacts. Resistor (R_p) or (R_{sh}) is the shunt resistance. Applying Kirchhoff's Law to the electric circuit results in equation (6.1).

$$I_{cell} = I_{ph} - I_d - I_p \quad (6.1)$$

where I_{cell} is the total current delivered from the solar cell. I_{ph} is the photocurrent generated when the solar cell is exposed to light. I_d is the current flowing through the diode. And I_p is the shunt current due to the shunt resistor branch.

Using the Shockley diode equation and the Ohm's law; expression (6.1) turns into Eq. (6.2).

$$I_{Cell} = I_{ph} - I_o \left\{ \exp \left(\frac{q(V + I R_s)}{n K T_c} \right) - 1 \right\} - \left(\frac{V + I R_s}{R_s} \right) \quad (6.2)$$

Where, $q = 1.602 \times 10^{-19} \text{C}$ is the elementary charge; $k = 1.38 \times 10^{-23} \text{ J /K}$ is the Boltzmann constant; $n = 1.3$ ^[116] is the ideal constant diode factor for c-Si, T_c , is the temperature of the solar cell, I_o is the diode saturation current; and R_s , R_p are the series and shunt resistance, respectively. Solving equation (6.2), the current and voltage of a single solar cell can be determined. A solar module

is the result of various solar cells connected in series and parallel to build up its voltage and current level. Considering a number of solar cells in series N_s , and a number of cells connected in parallel N_p , equation (6.2) turns in to equation (6.3).

$$I_A = N_p I_{ph} - I_o N_p \left[\exp \left(\frac{q(V_A + I_A \frac{N_s}{N_p} R_s)}{N_s K T_c} \right) - 1 \right] - \frac{V_A + I_A \frac{N_s}{N_p} R_s}{\frac{N_s}{N_p} R_p} \quad (6.3)$$

Where I_A and the V_A are the total current and voltage respectively, generated from the PV array. I_{ph} , I_d , R_s , R_p are unknown parameters intrinsic of each PV panel. The method to calculate these values applied in this thesis is adopted from the study of *Ti an et al.* ^[91], where a detailed explanation is presented. In the following sections the approach of determination of the values for I_{ph} , I_d , R_s , R_p is presented. Photo-current (I_{ph}).

The photocurrent is a function of the temperature and solar irradiance. Equation (6.4) is an empirical mathematical expression that defines the behavior of the photocurrent, presented by *Ti an et al.* ^[91]

$$I_{ph} = I_{phSTC} \left(\frac{G}{G_{STC}} \right) [1 + \alpha_T (T_C - T_{STC})] \quad (6.4)$$

In equation (6.4), $I_{ph,STC}$ is the photocurrent value at standard test conditions (STC). Many studies use the approximation of $I_{ph,STC} = I_{sc}$. The relative temperature coefficient of the short circuit current α_T is a parameter given by the manufacturer. $G_{STC} = 1000 \text{ W /m}^2$, is the

radiance at AM1.5 spectrum; G , is the actual solar irradiance in W/m^2 ; and $T_{STC} = 25^\circ C$, is the temperature at STC.

Consequently, the photocurrent of a solar cell under any irradiance and temperature can be determined using Eq. (6.4).

Saturation current (I_d):

The diode saturation current is a temperature dependent parameter intrinsic of a solar cell. An empirical mathematical expression defines the saturation current as equation (6.5).

$$I_d = I_{d,STC} \left[\frac{T}{T_{STC}} \right]^3 \exp \left[\frac{E_{g,STC}}{KT_{STC}} - \frac{E_g}{KT} \right] \quad (6.5)$$

where, $I_{d,STC}$, is the diode current at STC. This value can be determined using the method proposed by Tian et al. [91]. E_g , STC stands for the band gap energy at STC. And, E_g , is the energy band gap of crystalline silicon, which is temperature dependent and can be empirically described by Eq. (6.6).

$$E_g = 1.16 - 7.021 \times 10^{-4} \left(\frac{T_c^2}{T_c - 1108} \right) \quad (6.6)$$

Solar cell temperature:

Irradiance and ambient temperature modify the operational solar cell temperature. Masters et al. [116] proposes an empirical mathematical expression to determine the cell's temperature by Eq. (6.7). Where, T_{amb} is the ambient temperature, $G=1000 W/m^2$, is the solar irradiance and NOCT is the nominal operating cell temperature of the panel. The NOCT represents the temperature value reached by the solar cell when it operates at solar irradiance of $800 W/m^2$, wind speed of $1 m/s$, and air temperature of $20^\circ C$.

$$T_C = T_{amp} + \left(\frac{NOCT - 20^\circ C}{800} \right) G \quad (6.7)$$

Equations (6.4), (6.5), (6.6) and (6.7) can be used to model the performance of a PV module.

The unknown parameters in equations (6.4), (6.5), (6.6) and (6.7) can be determined using the mathematical model proposed by Tian et al. [91] and the following boundary conditions:

1. Open-circuit conditions where $I_{pv} = 0$ and $V_{pv} = V_{oc}, ref$;
2. Short-circuit condition where $I_{pv} = I_{sc}, ref$ and $V_{pv} = 0$;
3. Maximum operation points where $V_{pv} = V_{mpp}$ and $I_{pv} = I_{mpp}$;
4. The derivative of power with respect to voltage at MPP

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$\partial P / \partial v = 0$ and

5. Condition that guarantees that the temperature coefficient of the open-circuit voltage is correctly predicted by $\beta T = \partial V_{oc} / \partial T$.

Table (6.1): Specification of the PV panel.

Maximum Power – Pmax [Wp]	610	615	620	625	630	635
Maximum Power Voltage – Vmp [V]	40.56	40.56	40.56	40.56	40.56	40.56
Maximum Power Current – Imp [A]	15.04	15.04	15.04	15.04	15.04	15.04
Open-circuit Voltage – Voc [V]	48.63	48.63	48.63	48.63	48.63	48.63
Short-circuit Current – Isc [A]	16.01	16.01	16.01	16.01	16.01	16.01
Module Efficiency STC [%]	22.58	22.58	22.58	22.58	22.58	22.58
Power Tolerance	0 ~ + 3 %					
Temperature Coefficients of Pmax	-0.29 %/°C					
Temperature Coefficients of Voc	-0.25 %/°C					
Temperature Coefficients of Isc	0.045 %/°C					

Figures 6.4 and 6.5 show the I-V curve of the PV panel, generated with the model. The model has the flexibility to simulate any PV module configuration using all the possible irradiance and temperature conditions.

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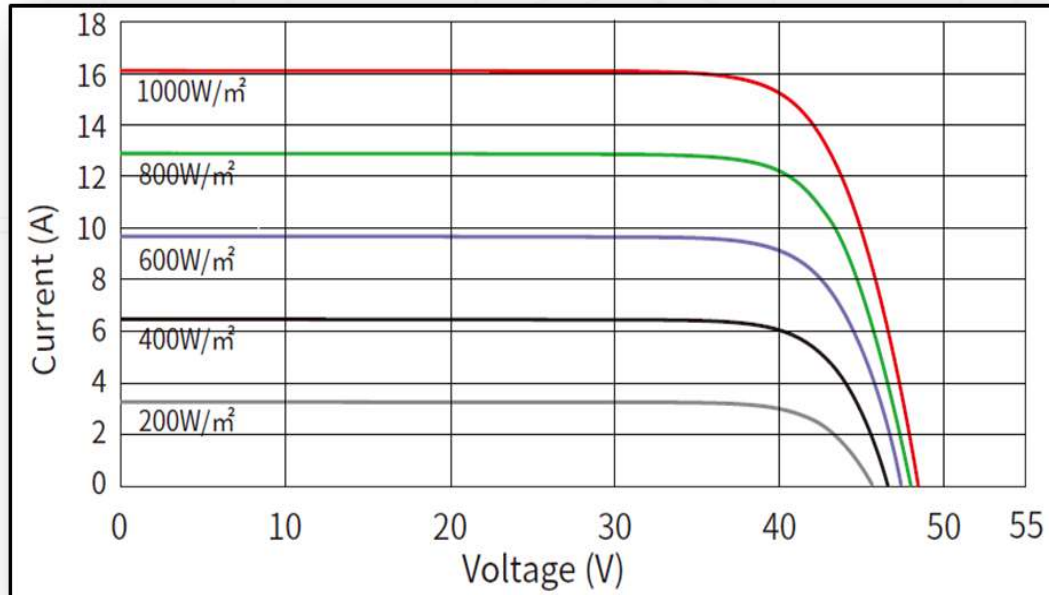


Figure (6.4): Current-voltage characteristic curve of a Jinko Solar 610 – 635 module panel.

Maximum power increases with increasing irradiance

Maximum power voltage changes little with irradiance

Current increases with
constant resistance

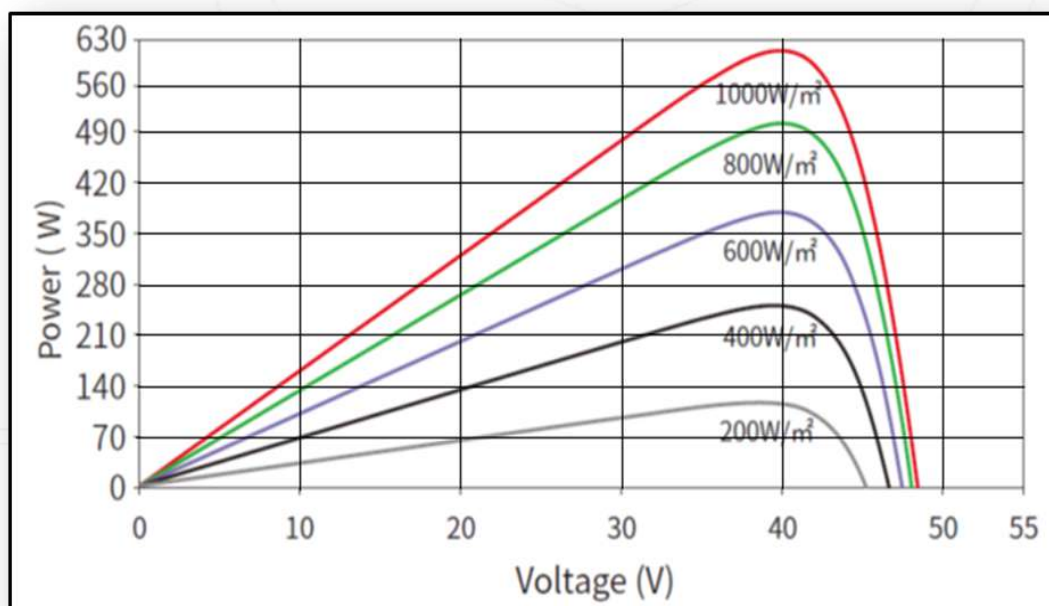


Figure (6.5): Power-voltage characteristic curve of a Jinko Solar 610 – 635 module panel.

As can be seen in the P-V characteristics above, the maximum output power reduces with reducing irradiance. There is also little reduction in the V_{OC} of the module. Similarly, in the I-V characteristics curves, we can see that there is a little increase in the V_{OC} with increasing irradiance. Also, the I_{SC} increases significantly with the increasing irradiance levels.

6.3.2 .PEM Electrolyzer Model:

The system produces hydrogen via water electrolysis using a proton exchange membrane (PEM) electrolyzer. Chapter 5 provides the important electrochemical and thermodynamic fundamentals involved in the electrolysis process. The electrolyzer model aims to mimic the behaviour of a real component under certain voltage and current conditions. Understanding the performance of the electrolyzer is important to assess the power consumption and hydrogen production of the system. Moreover, the model provides information about the electrolyzer performance under different conditions like temperature and pressure. The developed model of the PEM electrolyzer operation is taken from a study proposed by Awasthi et al. ^[92] Current, temperature and pressure are the external parameters taken as inputs for the electrolyzer model. Additionally, the electrolyzer parameters used as input for the model. As a result, the output variables are the operational cell voltage, water consumption, oxygen, and hydrogen production. A block representation of the model with its inputs and outputs

signals is presented in Figure 6.6. A detailed water PEM electrolyzer model involves mass transfer phenomena and electrochemical reactions.

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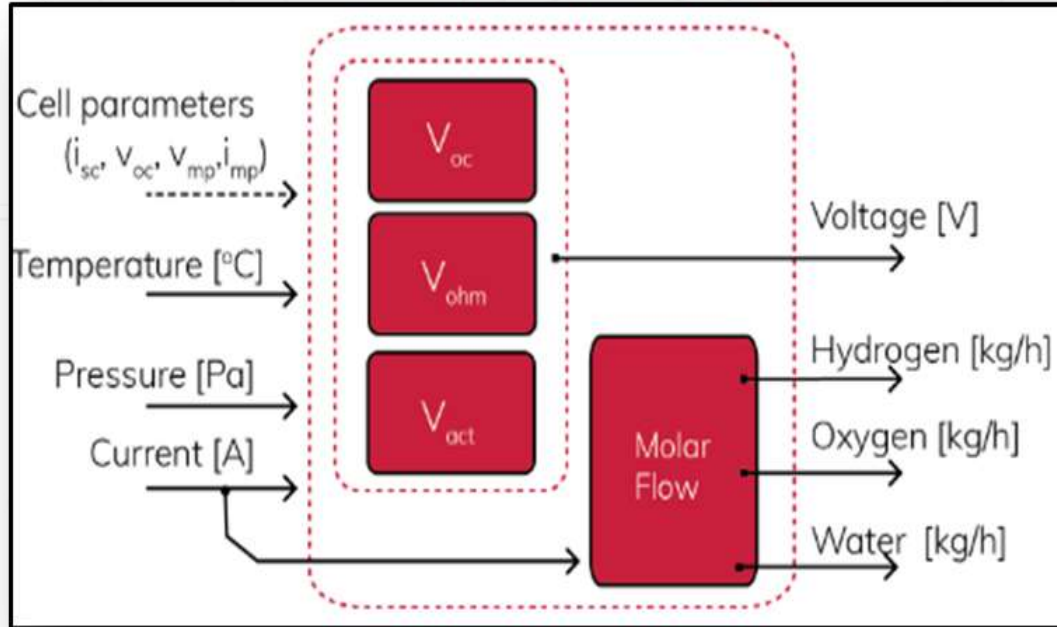


Figure (6.6): electrolyzer model, representing the input and output variables.

Table 6.2 summarizes the important characteristics of a PEM electrolyzer from the Electrolyzer manufacturer NEL. They manufacture PEM Electrolyzers with the best performance in terms of operating pressure (up to 30 bar), hydrogen flow rate (up to 492 Nm³/h), specific energy consumption (4.5 kWh/Nm³), partial load range (10–100%) and stack power (up to 2.5 MW) ^[55].

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Table (6.2) NEL: PEM Electrolyzer technical specification (55).

Characteristics	Specifications
Model	MC250
Rated stack power	1.25 MW
Average power consumption at stack per mass of H ₂ gas produced	50.4 kWh/kg
Lifetime	70,000 – 80,000h
Efficiency*	78%
Start-up time (from off state)	<5 min
Ramp up time (minimum to full load)	<15 sec
Production capacity dynamic range	10 to 100%
Hydrogen production at rated power	246 Nm ³ /h or 22.12 kg/h
Purity	99.95%
Output pressure	30 bar
Water consumption at maximum production	222 l/h

*Considering the HHV of hydrogen

6.3.3 Storage Tank Model:

The hydrogen produced by the electrolyzer is stored in a container. A steel storage tank was selected as the most suitable option because it is relatively small and cheap. This model determines the amount of hydrogen and pressure inside the tank. The amount of gas inside the tank helps to determine the optimal capacity for storage of any hydrogen production rate. This model is developed based on the study from Al-Refai et al. ^[93]. Hydrogen can be considered as ideal gas, since the operational temperature and pressure are in the range where this gas behaves as an ideal gas. Figure 6.7 shows the storage tank model, representing the input and output signals.

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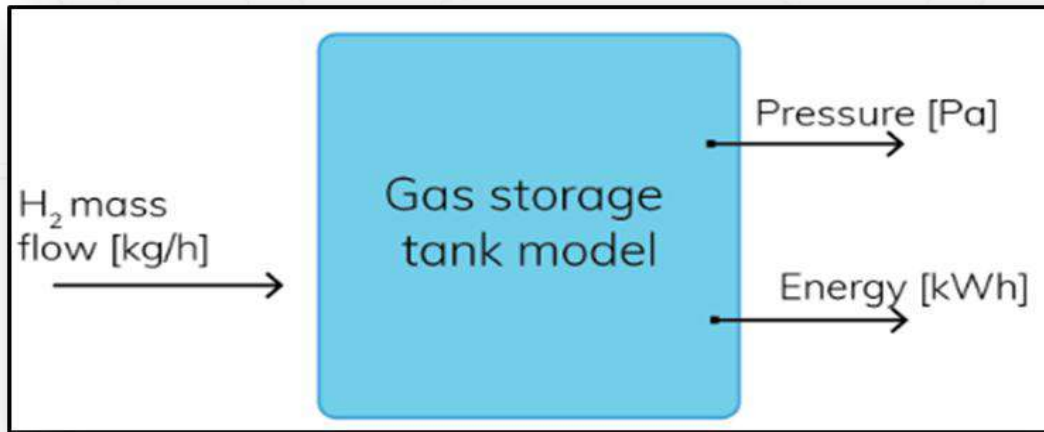


Figure (6.7) The storage tank model, representing the input and output signals.

6.4 Simulink Block Diagrams of the System:

Research on photovoltaic energy as energy source in various applications has increasing nowadays. It is clean, renewable and essential sustainable resources which make it suitable to be used as an alternative energy source due to finite source of fossil fuels and coals. Libya solar radiation is high by world standard. Power output of PV module is directly proportional to solar radiation. The simulation model is capable of handling various scenarios. Figure 6.8 presents the Simulink model of the solar model, DC/DC buck converter, electrolyzer, and hydrogen tank, with their mathematical models discussed in earlier sections.

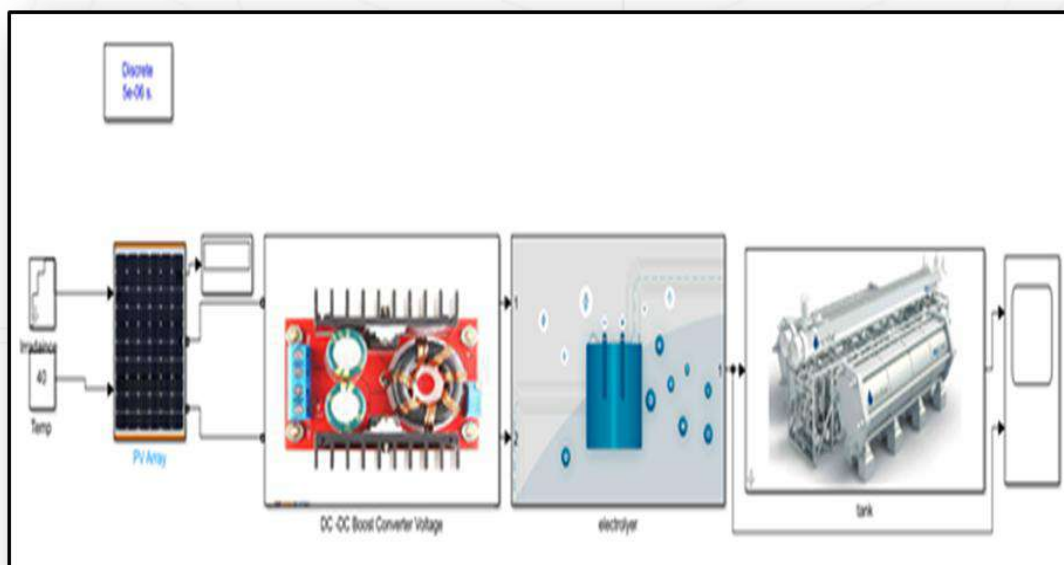


Figure (6.8): Simulink model for the solar hydrogen production.

Hence, The City of Zliten was chosen as best location to install PV module, the strength of solar radiation needs to be considered. Figure 6.9 shows the location and groundwater in Zlitan. Besides that, environmental factors and local climate such as humidity, temperature and wind also need to be considered as it will affect the output power of PV module. These effects are shown clearly in this Simulation result where the performances of PV module depend on the amount of solar radiation also the temperature of surrounding. Modeling and simulation of PV module helps in better understanding in terms of the behavior and characteristics. These methods effectively used in predicting the behavior of PV module vary in environmental conditions.

6.5 Data Acquisition and Use:

From the Meteorological Center for the western region of Tripoli and its suburbs. specifically, the city of Zliten because of its central location which is a city close to the coast and has abundant natural resources such as groundwater, temperature, and the amount of radiation. The total daily incident shortwave solar energy reaching the surface of the ground over a wide area, taking full account of seasonal variations in the length of the day, the elevation of the Sun above the horizon, and absorption by clouds and other atmospheric constituents. Shortwave radiation includes visible light and ultraviolet radiation. The average daily incident shortwave solar energy experiences extreme seasonal variation over the course of the year.

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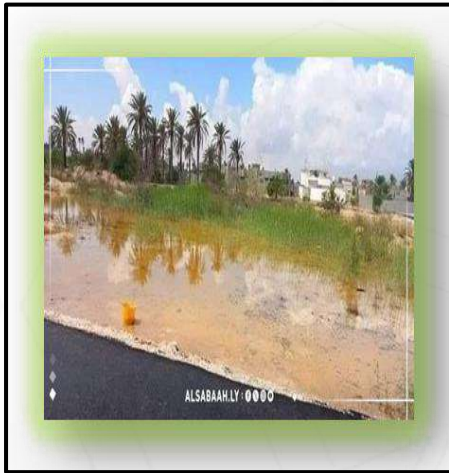
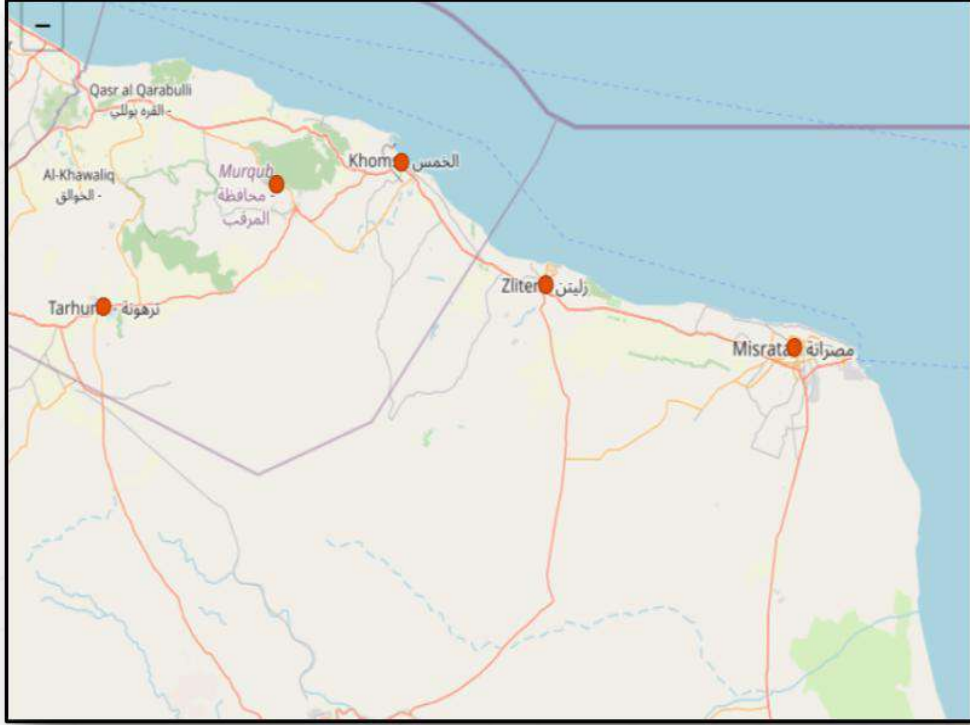


Figure (6.9) shows the location and groundwater in Zlitan.

The brighter period of the year lasts for 3.5 months, from May 7 to August 23, with an average daily incident shortwave energy per square meter above 7.1 kWh. The brightest month of the year in Zlitan is July, with an average of 8.1 kWh. The darker period of the year lasts for 3.3 months, from October 30 to February 7, with an average daily incident shortwave energy per

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square meter below 4.0 kWh. The darkest month of the year in Zliten is December, with an average of 3.0 kWh. The best tilt angle of solar panels in this city at an angle was 30° . Figure 6.10 shows the average daily shortwave solar energy reaching the ground per square meter.

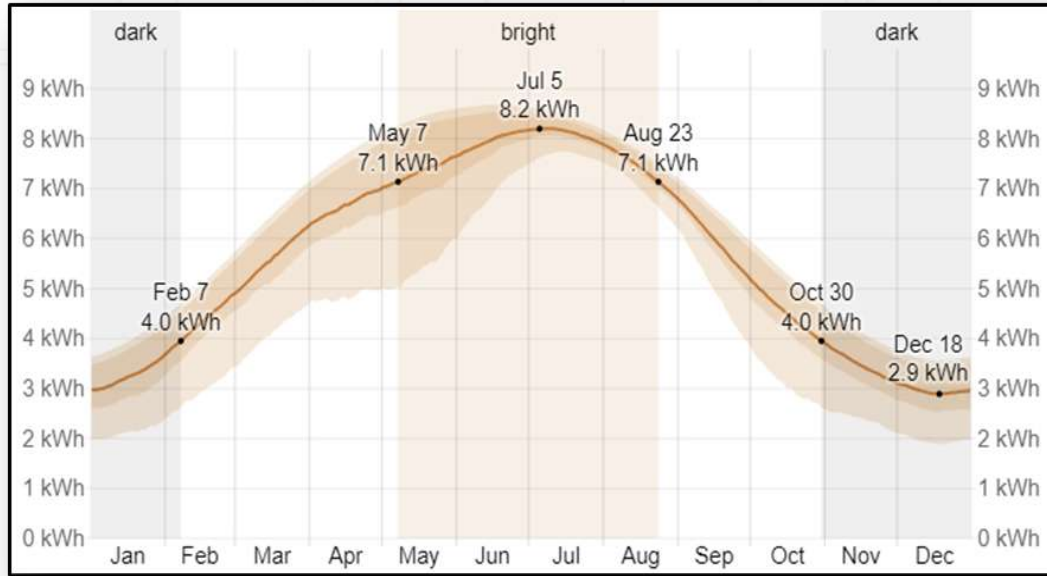


Figure (6.10) The average daily shortwave solar energy reaching the ground per square meter

6.6 PV Energy Generation:

The simulation run in this section, and uses irradiance data on an hourly basis from Zliten, the highest level of irradiance happens during summer. The power generation by the system for the period of a year is shown in Figure 6.11 and the annual power production is 3094200 kWh/year.

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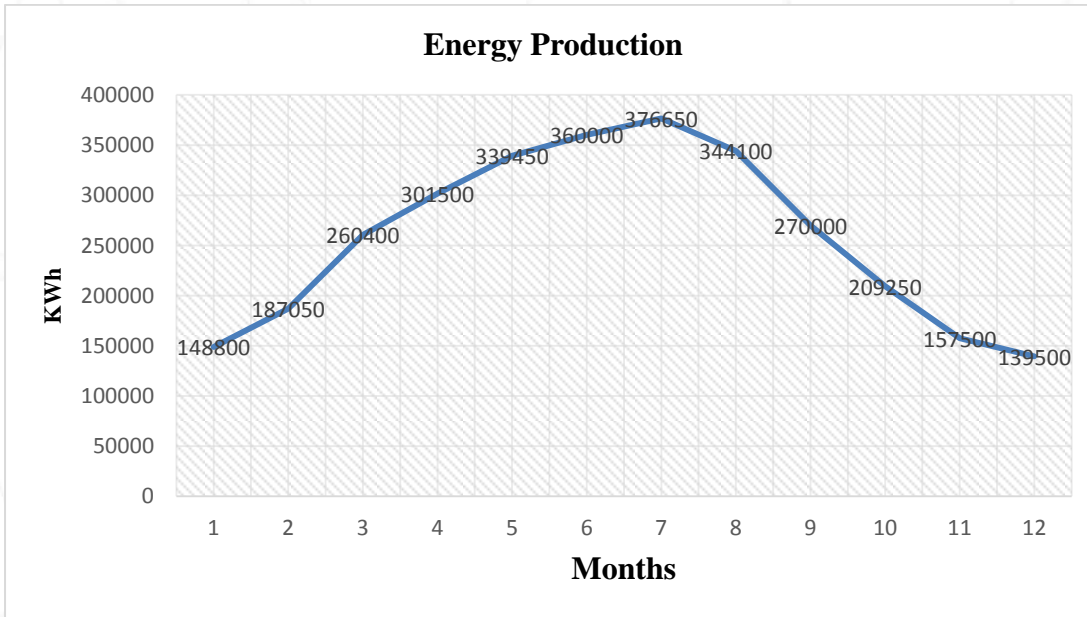


Figure (6.11) The power generation by the system

Hydrogen Production:

The generated power by the PV module is used to produce hydrogen. The tailored PV module provides the current and voltage to the Electrolyzer. The production of hydrogen is proportional to the current delivered by the PV module. The more current delivered by the PV module, the higher the hydrogen production from the Electrolyzer. Over the period of a year, the system produces 45629.136 kg of hydrogen, as shown in Figure 6.12.

The hydrogen production in the system is limited to the Electrolyzer capacity. The Electrolyzer capacity is 1.25 MW. All the power production higher than 1.25 MW cannot be used to produce hydrogen. Hydrogen cannot be produced with the energy surplus because it oversaturates the Electrolyzer's capacity. Hence the component sizing is crucial for an optimal system design. This issue can be solved by over-sizing the Electrolyzer capacity or by adding.

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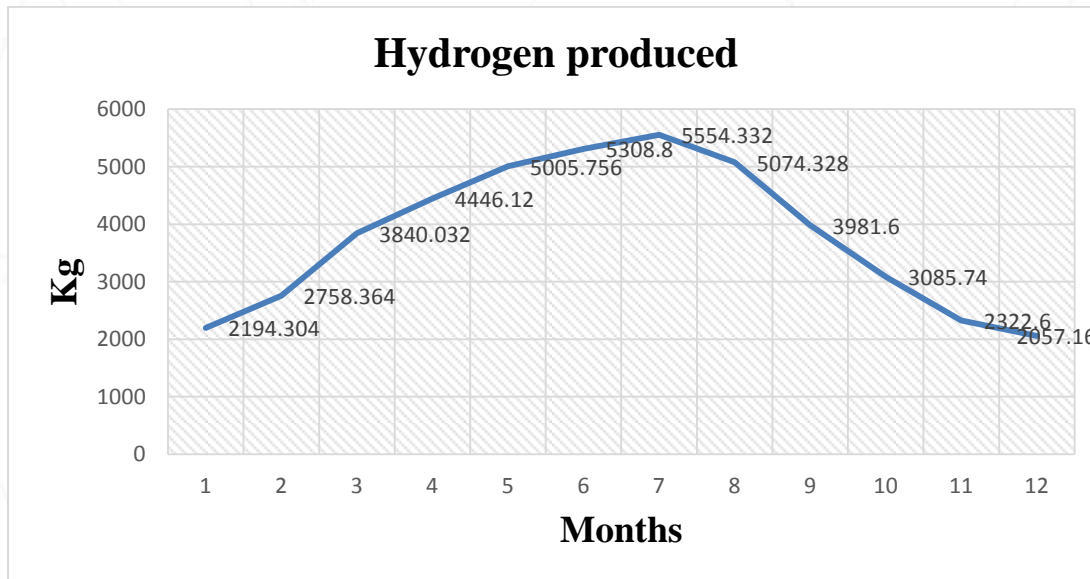


Figure (6.12). The hydrogen production in the system

An energy storage component to the system. The hydrogen production is directly proportional to the irradiance levels. During summer when there are higher irradiance levels, the hydrogen production increases. Figure 6.12 shows how the rate of hydrogen production increases significantly during the period when there is more solar power available. During winter (left/right area in Figure 6.12) the hydrogen production is minimal. Additionally, as part of the Electrolysis process, oxygen is produced in a total amount of 45629.136 Kg.

The water consumption corresponding to the generated hydrogen and Oxygen is 410662.224 Kg of water. Understanding the electrolysis process is essential because both water and oxygen are substances that are always present during the hydrogen production figure 6.13 shows the amount of hydrogen and oxygen produced by the system and water required. Oxygen can be reused for medical applications or to generate electricity when combining with hydrogen using a fuel cell. Also, Over the period of a year, the system produces 365033.088 kg of Oxygen. Table 6.3 shows the energy generated by the PV system and the hydrogen and oxygen produced.

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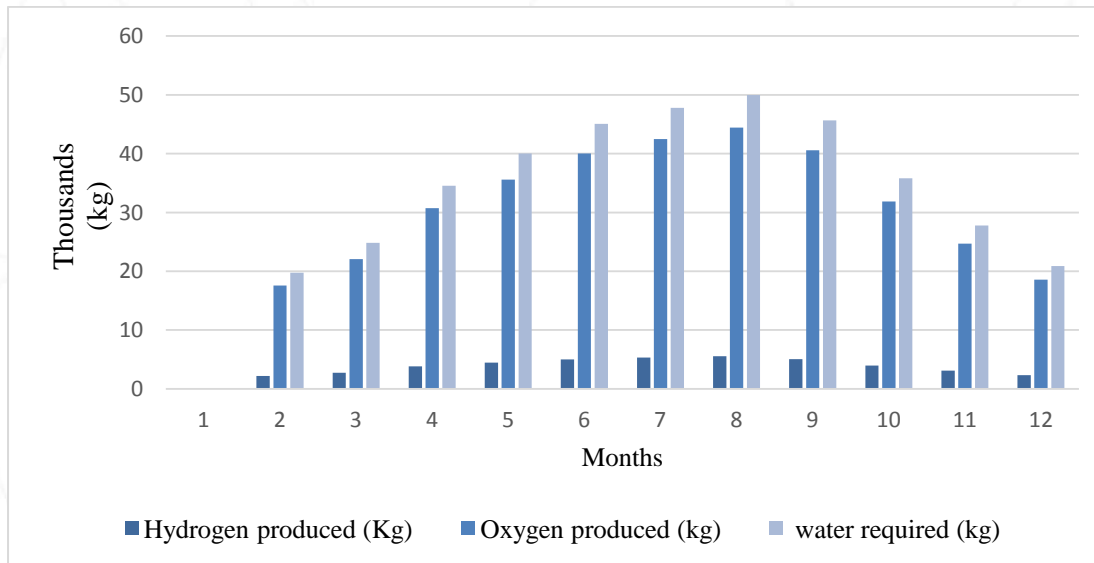


Figure (6.13) shows the amount of hydrogen and oxygen produced by the system and water required

Table 6.3 the system details:

Table (6.3) the system details.

Mon ths	PV Capa city (kW)	Peak Sun Hour s (h/da y)	Energ y Produ ced (kWh/ day)	Hydrogen produced (Kg) in Peak Sun Hours	Oxygen produced (kg)	Energy Required kWh	The water required (kg) to produce H2 and O
Jan	1500	3.2	148800	2194.304	17554.432	110592.9216	19748.736
Feb	1500	4.3	187050	2758.364	22066.912	139021.5456	24825.276
Mar	1500	5.6	260400	3840.032	30720.256	193537.6128	34560.288
Apr	1500	6.7	301500	4446.12	35568.96	224084.448	40015.08
May	1500	7.3	339450	5005.756	40046.048	252290.1024	45051.804
Jun	1500	8	360000	5308.8	42470.4	267563.52	47779.2
Jul	1500	8.1	376650	5554.332	44434.656	279938.3328	49988.988
Aug	1500	7.4	344100	5074.328	40594.624	255746.1312	45668.952

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Sep	1500	6	270000	3981.6	31852.8	200672.64	35834.4
Oct	1500	4.5	209250	3085.74	24685.92	155521.296	27771.66
Nov	1500	3.5	157500	2322.6	18580.8	117059.04	20903.4
Dec	1500	3	139500	2057.16	16457.28	103680.864	18514.44
			309420				
		0		45629.136	365033.088	2299708.454	410662.224

To calculate the energy production for a 1.5 MW PV system with an average daily incident shortwave energy of 8.2 kWh/m²/day, we follow a similar method as before:

Simplified Approach Using Solar Hours:

Since 8.2 kWh/m²/day is approximately equal to 8.2 peak sun hours, we can multiply the system's capacity by the number of sun hours.

$$\text{Energy Produced (kWh/day)} = \text{PV Capacity (kW)} \times \text{Peak Sun Hours (h/day)}$$

Given:

- PV Capacity = 1500 kW (1.5 MW)
- Solar Hours = 8.2 hours/day

$$\text{Energy Produced (kWh/day)} = 1500 \text{ kW} \times 8.2 \text{ h/day} = 12,300 \text{ kWh/day}$$

Annual Energy Production:

To find the total energy production per year:

$$\text{Energy Produced (kWh/year)} = 12,300 \text{ kWh/day} \times 365 \text{ days/year} = 4,489,500 \text{ kWh/year} \approx 4.49 \text{ GWh/year}$$

Conclusion:

- Daily Energy Production: 12,300 kWh/day
- Annual Energy Production: ~4.49 GWh/year

This shows that with 8.2 kWh/m²/day of solar irradiance, the 1.5 MW PV system can generate approximately 12,300 kWh/day or about 4.49 GWh/year.

1.5MW pv system how much energy can produce when an average daily incident shortwave energy per square meter above 7.1 kWh.

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To calculate the energy a 1.5 MW PV system can produce under the given conditions, we can use the following formula:

Energy Produced (kWh/day) =

PV Capacity (kW) \times Solar Irradiance (kWh/m²/day) \times area of the PV panels (m²) \times Efficiency

However, we are not given the area of the PV system or its efficiency directly, so we can assume a few things based on typical values for PV panels:

- PV Capacity: 1.5 MW = 1500 kW
- Solar Irradiance: 7.1 kWh/m²/day
- Efficiency: Let's assume a typical efficiency of 15-20% for the PV panels.

To simplify the calculation for the total energy generated by the system, we can assume that the entire system captures and converts solar energy uniformly over its rated power. In this case, we calculate the energy using just the rated power and available sunlight.

Formula:

Energy Produced (kWh/day) = PV Capacity (kW) \times Solar Hours (h/day)

Given:

- PV Capacity = 1500 kW (1.5 MW)
- Solar Hours = 7.1 hours/day (since 7.1 kWh/m²/day is equivalent to hours of full sun per day)

Energy Produced (kWh/day) = 1500 kW \times 7.1 h/day = 10,650 kWh/day

Thus, the 1.5 MW PV system can produce 10,650 kWh per day under an average daily incident shortwave energy of 7.1 kWh/m².

For PEM electrolyzer MC250 how much rated power needed to produce rated H₂ gas and how much water needs.

The power and water requirements for a PEM electrolyzer, such as the MC250, depend on the system's efficiency and hydrogen production rate. Let's break it down into key details:

1. Power Requirement:

For a PEM electrolyzer, the general energy requirement is about 50 to 55 kWh per kilogram of hydrogen produced, depending on efficiency. The MC250 electrolyzer likely has a specific rated hydrogen production capacity (e.g., Nm³/h of H₂).

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- **Rated hydrogen production:**

If the rated hydrogen production is provided (e.g., in Nm³/h or kg/h), we can estimate the required power. The energy consumption is around 50–55 kWh/kg of H₂.

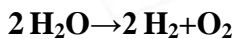
For example, if the MC250 produces 1 Nm³/h of hydrogen (approximately 0.0899 kg/h), the required power would be around:

- $0.0899 \text{ kg/h} \times 55 \text{ kWh/kg} = 4.945 \text{ kW}$.

This means to produce 1 Nm³/h of hydrogen, the system would need about 4.95 kW of electrical power.

2. Water Requirement:

The water consumption for hydrogen production follows the stoichiometric equation:



To produce 1 kg of hydrogen, 9 kg of water is required.

Using the same example:

- For 1 Nm³/h of hydrogen (0.0899 kg/h of hydrogen), the water required would be:
 $0.0899 \text{ kg/h} \times 9 = 0.8091 \text{ kg of water/h}$
- Thus, around 0.8091 liters of water per hour would be needed to produce 1 Nm³/h of hydrogen.

If you have the exact rated hydrogen production capacity of the MC250 electrolyzer, I can provide a more precise calculation.

If the exact rated hydrogen production capacity of the MC250 electrolyzer at rated power is 22.12 kg/h. how much energy and water need for 8.2 hours of operation.

Given the exact rated hydrogen production capacity of the MC250 electrolyzer at 22.12 kg/h, we can calculate the energy and water requirements for 8.2 hours of operation.

1. Hydrogen Production in 8.2 Hours:

The total hydrogen produced in 8.2 hours is:

$$22.12 \text{ kg/h} \times 8.2 \text{ hours} = 181.384 \text{ kg of H}_2.$$

2. Energy Requirement:

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For PEM electrolyzers, the energy consumption is typically 50 to 55 kWh per kg of hydrogen.

- At 50 kWh/kg:

$$181.384 \text{ kg} \times 50 \text{ kWh/kg} = 9,069.2 \text{ kWh.}$$

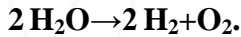
- At 55 kWh/kg:

$$181.384 \text{ kg} \times 55 \text{ kWh/kg} = 9,976.12 \text{ kWh.}$$

So, the energy requirement for 8.2 hours of operation is between 9,069.2 kWh and 9,976.12 kWh, depending on the efficiency.

3. Water Requirement

Water consumption for hydrogen production follows the stoichiometry of water splitting:



- To produce 1 kg of hydrogen, 9 kg (or 9 liters) of water is required.

The water required to produce 181.384 kg of hydrogen is:

$$181.384 \text{ kg of H}_2 \times 9 \text{ liters of water/kg of H}_2 = 1,632.456 \text{ liters of water.}$$

4. Conclusion:

For 8.2 hours of operation at full capacity:

- The energy requirement is between 9,069.2 kWh and 9,976.12 kWh.
- The water requirement is 1,632.456 liters (1.63 m³) of water.

If the exact rated hydrogen production capacity of the MC250 electrolyzer at rated power is 22.12 kg/h. how much energy and water need for 8.1 hours of operation and how much oxygen can get .

To calculate the energy, water consumption, and oxygen production for 8.1 hours of operation of the MC250 PEM electrolyzer, we can use the provided rated hydrogen production capacity and some fundamental relationships between hydrogen, water, and energy during electrolysis.

Given:

- Hydrogen production rate: 22.12 kg/h
- Operating time: 8.1 hours

1. Calculate Total Hydrogen Production:

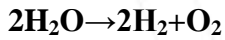
The total hydrogen produced over 8.1 hours is:

$$\text{Total H}_2 = \text{Production rate} \times \text{Operating time} = 22.12 \text{ kg/h} \times 8.1 \text{ h} = 179.172 \text{ kg}$$

So, 179.172 kg of hydrogen will be produced in 8.1 hours.

2. Determine Water Consumption:

For every kilogram of hydrogen produced by electrolysis, about 9 kg of water is consumed because of the stoichiometric relationship in the water-splitting reaction:



Thus, the total water needed for 179.172 kg of hydrogen is:

Water consumption = $179.172 \text{ kg H}_2 \times 9 \text{ kg water/kg H}_2 = 1,612.548 \text{ kg of water}$

Since the density of water is 1 kg/L, this is also 1,612.548 liters of water.

3. Determine Energy Required:

The energy required to produce hydrogen via electrolysis is typically around 50 kWh per kilogram of H_2 .

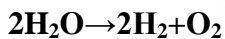
Thus, the total energy required to produce 179.172 kg of hydrogen is:

Energy consumption = $179.172 \text{ kg H}_2 \times 50 \text{ kWh/kg H}_2 = 8,958.6 \text{ kWh}$

So, the electrolyzer will consume approximately 8,958.6 kWh of energy for 8.1 hours of operation.

4. Calculate Oxygen Production:

From the water-splitting equation:



For every 2 moles of H_2 produced, 1 mole of O_2 is produced.

- Molar mass of $\text{H}_2 = 2 \text{ g/mol}$, molar mass of $\text{O}_2 = 32 \text{ g/mol}$.
- This means for every 2 kg of H_2 produced, 16 kg of O_2 is generated (since the ratio of H_2 to O_2 by mass is 1:8).

Thus, for 179.172 kg of hydrogen, the oxygen produced is:

$\text{O}_2 = 179.172 \text{ kg H}_2 \times 8 = 1,433.376 \text{ kg of O}_2$

Summary of Results:

- Hydrogen produced: 179.172 kg.
- Water required: 1,612.548 liters (or kg).
- Energy required: 8,958.6 kWh.
- Oxygen produced: 1,433.376 kg.

Conclusion:

The study on green hydrogen production in Libya, with Zliten as a case study, demonstrates the potential of harnessing solar energy through photovoltaic (PV) systems for sustainable energy solutions. The integration of MATLAB simulations and Excel-based analyses yielded the following key insights:

- **Abundant Solar Resource:** Libya's high solar irradiance, especially in the Zliten region, makes it a prime location for solar energy exploitation. The month of July was the brightest month of the year in Zliten, with solar radiation rate of $8.1 \text{ kWh/m}^2/\text{day}$. The PV system design and simulations confirmed its capacity to generate substantial electricity for powering electrolyzers. Where the rate of electricity production was 3094200 KWh/year .
- **Hydrogen Production Efficiency:** MATLAB simulations showed a positive correlation between PV power output and hydrogen production rates. Where was the hydrogen production $45629.136 \text{ Kg/year}$. The efficiency of the hydrogen production system influenced by temperature and irradiance, remained within acceptable operational ranges for most of the year.
- One of the points concluded from this study is that the hydrogen production in the system is limited to the Electrolyzer capacity. The Electrolyzer capacity is 1.25 MW . All the power production higher than 1.25 MW cannot be used to produce hydrogen. Hydrogen cannot be produced with the energy surplus because it oversaturates the Electrolyzer's capacity. Also, the hydrogen production is directly proportional to the irradiance levels. During summer when there are higher irradiance levels, the hydrogen production increases. Additionally, as part of the Electrolysis process, oxygen is produced in a total amount of $45629.136 \text{ Kg/year}$. the water consumption corresponding to the energy generated hydrogen and Oxygen is $410662.224 \text{ Kg/year}$ of water. And the amount of energy that was needed for these outcomes was $2299708.454 \text{ KWh/year}$. Understanding the electrolysis process is essential because both water and oxygen are substances that are always present during the hydrogen production.

Recommendation:

This study highlights the feasibility and advantages of adopting solar PV-powered hydrogen production in Libya, serving as a blueprint for similar initiatives in other regions with abundant solar resources. Further research and pilot projects are recommended to optimize system designs, improve cost-efficiency, and integrate green hydrogen into Libya's broader energy strategy.

- **Environmental Impact:** The transition to green hydrogen can significantly reduce carbon emissions in Libya's energy sector, supporting the country's commitment to global sustainability goals and reducing dependence on fossil fuels.
- **Scalability and Reliability:** The modularity of PV systems and the adaptability of hydrogen storage make this approach scalable to meet local and regional energy demands. However, challenges such as intermittency of solar power and the need for efficient storage solutions must be addressed.
- **Policy and Infrastructure Needs:** Realizing the potential of green hydrogen in Libya requires supportive policies, investment in renewable energy infrastructure, and partnerships to enhance technical expertise.
- **Previous solar-to-hydrogen systems have been developed, but there is still need of more in-depth under-standing on the optimal operating conditions for each of the components. Moreover, the lack of information about its design laws for these types of systems is a limiting factor for the faster development of such a system. More detailed analysis, for such a system, will encourage development of more studying projects and allow this technology to fully deploy. Hence, more investigation to fill those gaps by providing new knowledge on a solar-to-hydrogen systems is crucial for a faster implementation of flexible renewable energies.**

Conclusion:

This study focused on the performance of Power output PV module because. The production of green hydrogen is proportional to the current delivered by the PV module. The results showed a clear dependent of PV on both temperature of the surrounding, and the solar radiation amount this was clear in the(I-V) curve. Effective PV module is required in developing Maximum Power Point Tracking (MPPT) method as it relies on the behavior of the PV module to works accurately. The simulated model for PV module is to have closer insight and detailed analysis. This study used some data from the Meteorological Center in the city of Tripoli. We did a simple study using Excel and got the best tilt angle for installing the solar panels, which was 30° and the best average radiation amount was 8.1KWh. and we used the configuration represents a simple setup in which the photovoltaic (PV) modules serve as the main power source, directly supplying energy to the electrolyzer, which acts as the load. The design features a 1.5 MW PV system directly coupled to a 1.25 MW polymer electrolyte membrane (PEM) electrolyzer. The PV array generates direct current (DC) electricity, which the electrolyzer uses to split water into hydrogen and oxygen.

The tested irradiance data in the simulation was from Zilten for the irradiance in hourly basis. The results showed that, the highest level of irradiance happens during summer and the annual power production is 3094200 kWh/year. Further, over the period of a year, the system produces 45629.136 kg of hydrogen.

One of the points concluded from this study is that the hydrogen production in the system is limited to the Electrolyzer capacity. The Electrolyzer capacity is 1.25 MW. All the power production higher than 1.25 MW cannot be used to produce hydrogen. Hydrogen cannot be produced with the energy surplus because it oversaturates the Electrolyzer's capacity. Also, the hydrogen production is directly proportional to the irradiance levels. During summer when there are higher irradiance levels, the hydrogen production increases. Additionally, as part of the Electrolysis process, oxygen is produced in a total amount of 45629.136 Kg/year.. the water consumption corresponding to the generated hydrogen and Oxygen is 410662.224 Kg/year of water. Understanding the electrolysis process is essential because both water and oxygen are substances that are always present during the hydrogen production.

References:

- 1- N. Yasser, H. El-Khozondar, G. Ghaboun, M. Khaleel, Z. Yusupov, A. Ahmed, A. Alsharif, 2023. Solar and wind atlas for Libya, International Journal of Electrical Engineering and Sustainability (IJEES), vol. 1, no. 3, pp. 27-43.
<https://ijeess.org/index.php/ijeess/article/view/44/20>.
- 2- A. Maka and J. Alabid, "Solar energy technology and its roles in sustainable development," Clean Energy, vol. 6, no. 3, pp. 476–483, Jun. 2022, doi: 10.1093/ce/zkac023.
- 3- RE Clarke, S Giddey, FT Ciacchi, SPS Badwal, B Paul, and J Andrews. Direct coupling of an electrolyser to a solar pv system for generating hydrogen. International Journal of Hydrogen Energy, 34(6):2531–2542, 2009. Denmark targets 100% renewable electricity by 2050, July 2016.,
URL http://www.climateactionprogramme.org/news/denmark_targets_100_renewable_electricity_by_2050.
- 4- WMO Statement on the State of the Global Climate in 2016. Technical Report 1189, 2016.
- 5- Denmark targets 100% renewable electricity by 2050, July 2016.
URL http://www.climateactionprogramme.org/news/denmark_targets_100_renewable_electricity_by_2050.
- 6- Fatemeh Homayouni, Ramin Roshandel, and Ali Asghar Hamidi. Sizing and performance analysis of standalone hybrid photovoltaic/battery/hydrogen storage technology power generation systems based on the energy hub concept. International Journal of Green Energy, 14(2):121–134, 2017.
- 7- Sherif, S 2003 principle of hydrogen energy product and storage and utilization (Journal of scientific and industrial research on Vol. 62) Jan –Feb pp. 46-63.
- 8- Zeng, k. and Zhang 2010 Recent progress in alkaline water electrolysis for hydrogen production and applications (Prog. Energy Combust Science Elsevier) 36 (307)..
- 9- Ullber, O Morner S.O. 1997 TRNSYS simulation Models for solar – hydrogen system (Solar energy Vol.59) No.4-6, pp.271-279.
- 10- Walsh F.C 2001 Electrochemical technology for environmental treatment and clean energy conversion (Pure appl.chem., Vol.73) No.12 pp.1819-1837.

- 11- Moriarty P, Honnery D. Hydrogen's role in an uncertain energy future. Int J Hydrogen Energy 2009; 34: 31 - 9.
- 12- New Hydrogen Economy - Hope or Hype?" World Energy Council, 2019.[Online]. Available: <https://www.worldenergy.org/assets/downloads/WEInsights-Brief-New-Hydrogen-economy-Hype-or-Hope-ExecSum.pdf>. [Accessed: 11-May-2021].
- 13 -Hydrogen: grey, blue, and BC green," Resource Works, 2020. [Online]. Available: <https://www.resourceworks.com/hydrogen-grey-blue>. [Accessed: 11-May-2021]. -
- 14 -]-From Grey and Blue to Green Hydrogen," TNO. [Online]. Available: <https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-industry/hydrogen-for-a-sustainable-energy-supply/>. [Accessed: 11-May-2021]
- 15 - ↑ "From Grey and Blue to Green Hydrogen," TNO. [Online]. Available: <https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-industry/hydrogen-for-a-sustainable-energy-supply/>. [Accessed: 11-May-2021].
- 16 -Wikimedia Commons,[Online] .available: [https://commons.wikimedia.org/wiki/File:Bituminous_coal_\(Vandusen_Coal,_Lower_Pennsylvanian;_Irish_Ridge_East_roadcut,_near_Trinway,_Ohio,_USA\)_3_\(33236930615\).jpg](https://commons.wikimedia.org/wiki/File:Bituminous_coal_(Vandusen_Coal,_Lower_Pennsylvanian;_Irish_Ridge_East_roadcut,_near_Trinway,_Ohio,_USA)_3_(33236930615).jpg).
- 17- New Hydrogen Economy - Hope or Hype?" World Energy Council, 2019. [Online]. Available: <https://www.worldenergy.org/assets/downloads/WEInsights-Brief-New-Hydrogen-economy-Hype-or-Hope-ExecSum.pdf>. [Accessed: 11-May-2021].
- 18- Largest power to gas facility in the world now operational with Hydrogenics technology. <http://www.hydrogenics.com/about-the-company/news-updates/2013/06/14/largest-power-to-gas-facility-in-the-world-now-operational-with-hydrogenics-technology>.
- 19- . Szyszka A. Ten years of solar hydrogen demonstration project at Neunburg vorm Wald, Germany. Int J Hydrogen Energy 1998; 23:849–60.
- 20- . Adolf J, Balzer CH, Louis J, Schabla U, Fishedick M, Arnold K, Pastowski A, Schüwer D (2017). Shell Hydrogen Study. Energy of the Future? Sustainable Mobility through Fuel Cells and H₂. Technical Report, January 2017. DOI: 10.13140/RG.2.2.31848.57604.
- 21- . Rivard E, Trudeau M, Zaghib K (2019). Hydrogen Storage for Mobility. A Review. Materials 12(12), 1944-1996. DOI: <https://doi.org/10.3390/ma12121973>.

- 22- . Berstad D, Stang JH and P Neksa (2009). Comparison criteria for large-scale hydrogen liquefaction processes. *International Journal of Hydrogen Energy* 34: 1560-1568. OI: <https://doi.org/10.1016/j.ijhydene.2008.11.058>.
- 23- Kang, D., Yun, S., & Kim, B. (2022). Review of the Liquid Hydrogen Storage Tank and Insulation System for the High-Power Locomotive. *Energies*, 15(12), 4357.
- 24- Nierman M, Drünert A, Kaltschmitt M and K Bonhoff (2019). Liquid organic hydrogen carriers (LOHCs)–techno-economic analysis of LOHCs in a defined process chain. *Energy and Environmental Science* 12: 290.DOI: <https://doi.org/10.1039/C8EE02700E>..
- 25- Y. Suyun, L. Ouyang and Z. Min, Hydrogen storage properties of preferentially orientated Mg-Ni multilayer film prepared by magnetron sputtering., *Rare Met.*, 2006, 25(6), 295–299 [CrossRef](#).
- 26- Rowsell, J. L. C., & Yaghi, O. M. (2015). Strategies for Hydrogen Storage in Metal – Organic Frameworks. *Minireviews*, 1055, 4670–4679. <https://doi.org/10.1002/anie.200462786>.
- 27- Gregorowicz, J., Peters, C., Arons, J., Friedrichs, G., Jaeschke, M. (1996). Phenomena related to the storage of natural gas in underground caverns. *Fluid Phase Equilibria* 117, 249-256.
- 28- Lattuada, R., Raper, J. (1998). Modelling of salt domes from scattered non-regular point sets. *Phys. Chem. Earth* 23, 273-277.
- 29- Micro-H2 [WWW Document], 2011. URL <http://www.microh2.ulg.ac.be/PROJECT1.html>(accessed 4.20.21).
- 30- Fabio Leccese. Published by The Open Fuel Cells Journal, 2013.
- 31- Technology Characterization – Fuel Cells by Ken Darrow, Rick Tidball, James Wang and Anne Hampson at ICF International, the U.S. Environmental Protection Agency and the U.S. Department of Energy. March 2015.
- 32- Fuel Cell Handbook by EG&G Technical Services, Inc. for U.S. Department of Energy dated Nov 2004.
- 33- An introduction to Fuel Cell Technology and Economics by Nigel Brandon and David Hart. Report published by the Centre for Energy Policy and Technology, Imperial College, London July 1999.

التقييمات الحرارية والاقتصادية للهيدروجين الأخضر في ليبيا باستخدام الألواح
الكهروضوئية الشمسية وجهاز التحليل الكهربائي الكهروضوئي والبوليمر الانعكاسي.

**Thermoeconomic Assessments of Green Hydrogen in Libya Using Solar Photovoltaics (PV) Panels
and PV&PEM Electrolyzer.**

- 34- Velazquez Abad, A; Dodds, PE; (2017) Production of Hydrogen. In: Abraham, MA, (ed.) Encyclopedia of Sustainable Technologies. (pp. 293-304). Elsevier: Amsterdam, Netherlands..
- 35- IEA (International Energy Agency) (2019), World Energy Investment 2019, IEA, Paris.
- 36- FCH-JU (2019). Hydrogen Roadmap Europe. A sustainable pathway for the European energy transition. Report from the EU Fuel Cells and Hydrogen Joint Undertaking. DOI: 10.2843/341510.
- 37- -DNV GL (2018). Energy Transition Outlook 2018. A global and regional forecast to 2050. URL: <https://eto.dnvgl.com/2018/>.
- 38- . Shell (2018). Sky scenario. Meeting the goals of the Paris Agreement. URL: https://www.shell.com/promos/business-customers-promos/download-latest-scenariosky/_jcr_content.stream/1530643931055/eca19f7fc0d20adbe830d3b0b27bcc9ef72198f5/shell-scenariosky.pdf.
- 39- Hodges JP, Geary W, Graham S, Hooker P, and R Goff (2015). Injecting hydrogen into the gas network – aliterature search. RR1047 Research Report. Health and Safety Executive 2015. UTL:
- 40- Dashtebayaz MD, Moghadam AE, Pishbin SI, Pourramezan M (2019). Investigating the effect of hydrogen injection on natural gas thermo-physical properties with various compositions. Energy 167: 235-245. DOI: <https://doi.org/10.1016/j.energy.2018.10.186>.
- 41- Nastasi B, Basso GL (2016). Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. Energy 110: 5-22. DOI: <https://doi.org/10.1016/j.energy.2016.03.097>.
- 42- Staffell I, Scamman D, Abad AV, Balcombe P, Dodds PE, Ekins P, Shah N, Ward K (2019). The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science 12: 463-491. DOI: 10.1039/c8ee01157e.
- 43- Alsubaie A, Fowler M, Elkamel A (2019). Hydrogen supply via power-to-gas application in the renewable fuel's regulations of petroleum fuels. The Canadian Journal of Chemical Engineering 97:7, 1999-2008. DOI: <https://doi.org/10.1002/ceej.23474>.
- 44- Wulf C, Linssen J, Zapp P (2018). Review of Power-to-Gas Projects in Europe. 12th International Renewable Energy Storage Conference, IRES 2018. Energy Procedia 155: 367-378. DOI: <https://doi.org/10.1016/j.egypro.2018.11.041>.

التقييمات الحرارية والاقتصادية للهيدروجين الأخضر في ليبيا باستخدام الألواح
الكهروضوئية الشمسية وجهاز التحليل الكهربائي الكهروضوئي والبوليمر الانعكاسي.

**Thermoeconomic Assessments of Green Hydrogen in Libya Using Solar Photovoltaics (PV) Panels
and PV&PEM Electrolyzer.**

- 45- URL.http://www.beatriceco.com/bti/porticus/bell/images/solar_battery2.gif.
- 46- Kunta Yoshikawa, Wataru Yoshida, Toru Irie, Hayato Kawasaki, Katsunori Konishi, Hirotaka Ishibashi, Tsuyoshi Asatani, Daisuke Adachi, Masanori Kanematsu, Hisashi Uzu, and Kenji Yamamoto. Solar En-ergy Materials and Solar Cells Exceeding conversion e ffi ciency of 26 % by heterojunction interdigitated back contact solar cell with thin fi lm Si technology. Solar Energy Materials and Solar Cells,,173(June)02017, 42-372017 ISSN 0927-0248. doi: 10.1016/j.solmat.2017.06.024. URL <https://doi.org/10.1016/j.solmat.2017.06.024>
- 47- Gregory F Nemet. Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy policy, 34(17):3218–3232, 2006
- 48- Renewable power: sharply falling generation costs. 2017. URL https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Nov/IRENA_Sharpely_falling_costs_2017.pdf?la=en&hash=124D0C6FF4AE247D8CFB4FF7F064F5F25432AC5B.
- 49- Saudi arabia gets cheapest bids for solar power in auction, October 2017 .URL <https://www.bloomberg.com/news/articles/2017-10-03/saudi-arabia-gets-cheapest-ever-bids-for-solar-power-in-auction>.
- 50- Johannes N Mayer, P Simon, Noha Saad Hussein Philipps, Thomas Schlegl, and Charlotte Senkpiel. Cur-rent and future cost of photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems (Fraunhofer ISE, Study on behalf of Agora Energiewende, Freiburg, 2015,(2015).
- 51- The Guardian. Time to shine: Solar power is fastest-growing source of new en-ergy. October 2017. URL. <https://www.theguardian.com/environment/2017/oct/04/solar-power-renewables-international-energy-agency>.
- 52- International Energy Agency. Renewables 2017. pages 1–16, 2017. URL <https://www.iea.org/publications/renewables2017/>
- 53- The Guardian. Time to shine: Solar power is fastest-growing source of new en-ergy. October 2017. URL. <https://www.theguardian.com/environment/2017/oct/04/solar-power-renewables-international-energy-agency>.
- 54- Fraunhofer Research Institute. Photovoltaics report. (July), 2017.
- 55- I E A Pvp's. Global installed PV capacity exceeds 300 GW, IEA PVPS The world' s cumulative PV capacity had surpassed. pages 2016–2017, 2016.

- 56- Eric Wesoff April, The International, Energy Agency, and Allow Gtm. IEA : Global Installed PV Capacity Leaps to 303 Gigawatts. pages 12–14, 2017
- 57- Snapshot Of and Global Photovoltaic. Snapshot of global photovoltaic markets. pages 1–16, 2017.
- 58-] Kunta Yoshikawa, Wataru Yoshida, Toru Irie, Hayato Kawasaki, Katsunori Konishi, Hirotaka Ishibashi, Tsuyoshi Asatani, Daisuke Adachi, Masanori Kanematsu, Hisashi Uzu, and Kenji Yamamoto. Solar En-ergy Materials and Solar Cells Exceeding conversion e ffi ciency of 26 % by heterojunction interdigitated back contact solar cell with thin fi lm Si technology. Solar Energy Materials and Solar Cells, 173(June:(
- 59- .2017 ,42–37ISSN 0927-0248. doi: 10.1016/j.solmat.2017.06.024. URL <https://doi.org/10.1016/j.solmat.2017.06.024>.
- 60- "Monocrystalline Solar Modules". Retrieved 27 August 2020.
- 61- L. Matejcek, Solar energy: estimates of energy potential and environmental issues, in: As] Edoff, Marika (March 2012). "Thin Film Solar Cells: Research in an Industrial Perspective". Ambio. 41 (2):112– 118. Bibcode:2012Ambio..41S.112E. doi:10.1007/s13280-012-0265-6. ISSN 0044-7447. PMC 3357764. PMID 22434436.
- 62- J. O. Bockris, B. E. Conway, E. Yeager and R. E. White, Comprehensive Treatise of Electrochemistry, vol. 2, New York: Springer, 1981
- 63- Berg H. Johann Wilhelm Ritter — the founder of scientific electrochemistry. Rev Polarogr 2008; 54:99–103.
- 64- Zhang J, Zhang L, Liu H, Sun A, Liu RS. Electrochemical technologies for energy storage and conversion. New York: Wiley; 2012.
- 65- Ursu´a, BHydrogen production with alkaline electrolyzers: Electrochemical modelling, electric power supplies and integration with renewable energies,[(in Spanish) Ph.D. dissertation, Dept. Electr.
- 66- Ursua, L. Gandia and P. Sanchis, "Hydrogen Production from Water Electrolysis: Current Status and Future Trends," Proceedings of the IEEE, vol. 100, no. 2, pp. 410-426, 2012
- 67- S. Grigoriev, V. Porembsky and V. Fateev, "Pure hydrogen production by PEM electrolysis for hydrogen energy,," International Journal of Hydrogen Energy, vol. 31, pp. 171-175, 200

- 68- C Riordan and R Hulstron. What is an air mass 1.5 spectrum? (solar cell performance calculations). In Photovoltaic Specialists Conference, 1990., Conference Record of the Twenty First IEEE, pages 1085–1088.IEEE, 1990.
- 69- S. Grigoriev, V. Porembsky and V. Fateev, "Pure hydrogen production by PEM electrolysis for hydrogen energy,," International Journal of Hydrogen Energy, vol. 31, pp. 171-175, 200.
- 70- .Millet, R. Ngameni, S.A. Grigoriev, N. Mbemba, F. Brisset, A. 1191- Ranjbari, *et al.* PEM water electrolyzers: from electrocatalysis to stack developmentInt. J. Hydrogen Energy, 35 (2010), pp. 5043-5052 [View PDFView articleView in ScopusGoogle Scholar](#).
- 71- D. Bessarabov, H. Wang, H. Li, N. Zhao PEM Electrolysis for Hydrogen Production: Principles and ApplicationsCRC press (2016)[Google Scholar](#)Koumi Ngoh, Simon & Njomo, Donatien, 2012. "[An overview of hydrogen gas production from solar energy,](#)" [Renewable and Sustainable Energy Reviews](#), Elsevier, vol. 16(9), pages 6782-6792.
- 72- A. Godula-Jopek (Ed.), Hydrogen Production by Electrolysis, Wiley-VCH, Weinheim (2015)[Google Scholar](#).
- 73- [2012 - PEM water electrolysis fundamentals](#).
- 74- "[2014 - Development of water electrolysis in the European Union](#)" (PDF). Archived from [the original](#) (PDF) on 2015-03-31. Retrieved 2014-12-03.
- 75- 1-Carmo, M; Fritz D; Mergel J; Stolten D (2013). "A comprehensive review on PEM water electrolysis". *International Journal of Hydrogen Energy*. 38 (12): 4901–4934. [doi:10.1016/j.ijhydene.2013.01.151](#)
- 76- Graves, C.; Ebbesen, S.D.; Mogensen, M.; Lackner, K.S. Sustainable hydrocarbon fuels by recycling CO₂ and H₂O with renewable or nuclear energy. *Renew. Sustain. Energy Rev.* 2011,15, 1–23. [CrossRef].
- 77- Russell, JH; Nuttall LJ; Ficket AP (1973). "Hydrogen generation by solid polymer electrolyte water electrolysis". American Chemical Society Division of Fuel Chemistry Preprints.
- 78- Slade, S; Campbell SA; Ralph TR; Walsh FC (2002). "[Ionic conductivity of an extruded Nafion 1100 EW series of membranes](#)" (PDF). *Journal of the Electrochemical Society*. 149.
- 79- Schröder, V; Emonts B; Janßen H; Schulze HP (2004). "Explosion Limits of Hydrogen/Oxygen Mixtures at Initial Pressures up to 200 bar". *Chemical Engineering & Technology*. 27 (8): 847–851. [doi:10.1002/ceat.200403174URL.http://www.beatriceco.com/bti/porticus/bell/images/solar_battery2.gif](#).

- 80- F. Barbir, "PEM electrolysis for production of hydrogen from renewable energy sources," Solar Energy, vol. 78, no. 5, pp. 661-669, 2005..
- 81- Bernholz, Jan (September 13, 2018). ["RWE's former, current and possible future energy storage applications"](#) (PDF). [RWE](#). p. 10. Total Efficiency: 70%, or 86% (usage of waste heat).
- 82- ITM – Hydrogen Refuelling Infrastructure – February 2017" (PDF). [level-network.com](#). Archived (PDF) from the original on 17 April 2018. Retrieved 17 April 2018. [dead link].
- 83- "Report and Financial Statements 30 April 2016" (PDF). [www.itm-power.com](#). Retrieved 17 April 2018.
- 84- Hongmei Tian, Fernando Mancilla-david, Kevin Ellis, Peter Jenkins, and Eduard Muljadi. A Detailed Performance Model for Photovoltaic Systems Preprint. (July), 2012.
- 85- Greig Chisholm and Leroy Cronin. Hydrogen from water electrolysis. Storing Energy: with Special Reference to Renewable Energy Sources, page 315, 2016.
- 86- 108-Ni Meng, KH Michael, and YC Dennis. Electrochemistry modeling of proton exchange membrane (pem)water electrolysis for hydrogen production. 2006.
- 87- Krishnan Rajeshwar, Robert McConnell, and Stuart Licht. Solar hydrogen generation. Toward a renewable energy future. Springer: New York, 2008.
- 88- Gilbert M Masters. Renewable and efficient electric power systems. John Wiley & Sons, 2013.
- 89- Pierre Millet and Sergey Grigoriev. Chapter 2 - water electrolysis technologies. In Luis M. Gandía, Gu-rutze Arzamendi, and Pedro M. Diéguez, editors, Renewable Hydrogen Technologies, pages 19 – 41. Elsevier, Amsterdam, 2013. ISBN 978-0-444-56352-1. doi: <https://doi.org/10.1016/B978-0-444-56352-1.00002-7>. URL <http://www.sciencedirect.com/science/article/pii/B9780444563521000027>.
- 90- Thomas L Gibson and Nelson A Kelly. Optimization of solar powered hydrogen production using photo-voltaic electrolysis devices. International journal of hydrogen energy, 33(21):5931–5940, 2008.
- 91- Hongmei Tian, Fernando Mancilla-David, Kevin Ellis, E Muljadi, and P Jenkins. Detailed performance model for photovoltaic systems: Preprint. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO., 2012.
- 92- A Awasthi, Keith Scott, and S Basu. Dynamic modeling and simulation of a proton exchange membrane electrolyzer for hydrogen production. International Journal of Hydrogen Energy,

التقييمات الحرارية والاقتصادية للهيدروجين الأخضر في ليبيا باستخدام الألواح
الكهروضوئية الشمسية وجهاز التحليل الكهربائي الكهروضوئي والبوليمر الانعكاسي.

**Thermoeconomic Assessments of Green Hydrogen in Libya Using Solar Photovoltaics (PV) Panels
and PV&PEM Electrolyzer.**

36(22):14779–14786 .2011,ISSN 0360-3199. doi: 10.1016/j.ijhydene.2011.03.045. URL
<http://dx.doi.org/10.1016/j.ijhydene.2011.03.045>.

93- ..Mustafa A Al-refai. Matlab / Simulink Simulation of Solar Energy Storage System. 8(2):297–
302, 2014

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