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STUDY AND DESIGN OF A HYDROGEN STATION

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شكر وعرفان

بسم الله الرحمن الرحيم

الحمد لله رب العالمين، الذي أكرمني بعونه وتوفيقه، فكان خير مُعينٍ في إتمام هذه الرحلة العلمية، وإخراج هذه المذكرة في أبهى صورة. لقد بدأت مسيرتي وأنا أرى يوم التخرج حلمًا يلوح في الأفق البعيد، وغايةً سعيتُ إليها بكل جدٍّ واجتهاد، فكانت هذه المذكرة زهرةً اجتنيها بعد عناء السنين، وحصاد فكرٍ وبحثٍ امتزجَا بعرق الجبين .

وإنّي إذ أقدِّم بين أيديكم ثمرة جهدي، أضع في طيّاتها عصارة أفكارٍ درسْتُها، ومعلوماتٍ جمعْتُها من شتّى المصادر، عسى أن تكون لَبِنةً في صرح العلم النافع .

وأيمَانًا منّي بأنَّ الشكر لله أوَّلًا ثمَّ للبشر، أتوجّه بأصدق عبارات الامتنان إلى :

الأستاذ المُلهِم "**حُسين عبد القادر**"، الذي كان نبراسًا يُضيء دربي، فلم يبخل عليَّ بتوجيهاته الحكيمة، ونقده الذي صقل أفكاري، ودعمه الأكاديمي الذي كان سندًا لي في كل خطوة .

أسرتي الغالية، ركني الآمن، الذين تحمَّلوا غيابي وصبروا على انشغالي، فكانوا جناحين حملاني إلى سماء النجاح، فردًا فردًا، لا أنسى لهم دعمًا قدَّموه ولا تضحيةً بذلوها .

أصدقائي الأعزّاء ومَن غرسوا فيَّ حب العطاء، الذين كانوا عونًا لي في السرّاء والضرّاء، يمدّون لي يدَ العون الماديِّ والمعنويِّ بلا حدود .

فلكم جميعًا، أهدي هذا الجهد المتواضع، راجيًا أن أكون قد وَفّيتُ جزءًا من حقّكم عليَّ، وأن أردَّ ولو ذرّةً من جميلكم الذي لا يُنسى.

إهداء

بعد فضل الله تعالى ...

إلى رمز العطاء والحكمة، صاحب السيرة العطرة والفكر المُستنير، الوالد الحبيب "**عمر**"، الذي كان له الفضل الأول في بلوغي مراتب العلم، أطال الله في عمره وحفظه ذخرًا لي .

إلى من غرست فيَّ حب التحدي، ووضعتني على درب العلم بلا تردد، الأم الغالية "**حورية**"، التي كانت نبع حنانٍ لا ينضب، ومصدر قوتي حتى صِرتُ ما أنا عليه، طيَّب الله ثراها، وأدام ذكراها الطيب في قلوب من عرفها .

إلى **إخوتي** الأعزاء، الذين كان لهم بالغ الأثر في تجاوزي الكثير من العقبات، فكانوا سندًا في الظلام ومُعينًا على الصعاب .

إلى **أساتذتي** الأفاضل، الذين لم يبخلوا عليَّ بتوجيهاتهم الثمينة، ومدّوا لي يد العون بكل سخاء، فكانوا شمعةً أضاءت دربي .

أهدي إليكم جميعًا ثمرة جهدي، راجيًا أن أكون عند حسن ظنكم .

خالد

ملخص

تهدف هذه المذكرة إلى إجراء دراسة شاملة حول تصميم محطة هيدروجين خضراء في الجزائر. تغطي هذه الدراسة الخلفية النظرية لمصدر الطاقة الهيدروجينية، وتحديد المتطلبات الوظيفية والجدوى الفنية، وتصميم المحطة وخطة صيانة قابلة للتطوير باستخدام أحدث تقنيات الذكاء الاصطناعي.

تركز الدراسة على الإمكانات الكبيرة للهيدروجين في التحول العالمي للطاقة، ودوره في تحقيق الحياد الكربوني واستراتيجية الجزائر في مجال الطاقات المتجددة. كما تقيّم الدراسة إنتاج الهيدروجين وتخزينه وتوزيعه وتطبيقاته المستقبلية، وتقدم خطة صيانة متكاملة تعتمد على تقنيات الذكاء الاصطناعي لضمان تشغيل المحطة بشكل مستدام وفعال. تقدم هذه الدراسة نموذجًا واقعيًا لمحطة هيدروجين تتكيف مع الظروف الجزائرية، مما يجعلها مصدرًا قيمًا للباحثين وصناع القرار في هذا المجال الواعد.

الكلمات المفتاحية:

الهيدروجين الأخضر، محطة هيدروجين، الطاقات المتجددة، الطاقة الشمسية، الطاقة الريحية، التحليل الكهربائي، محلل كهربائي قلوي، تخزين الهيدروجين، توزيع الهيدروجين، التحليل الوظيفي، مخطط FAST، منهجية SADT، تصميم ثلاثي الأبعاد، SolidWorks، الصيانة الذكية، الذكاء الاصطناعي، الصيانة التنبؤية، الانتقال الطاقوي، الجزائر

Abstract

The object of this thesis is to conduct a comprehensive study on the design of a green hydrogen station in Algeria. This study will cover the theoretical background of the hydrogen energy source, the identification of functional requirements and technical feasibility, the station design and a scalable maintenance plan using the latest artificial intelligence technologies.

The study focuses on the significant potential of hydrogen in the global energy transition, its role in achieving carbon neutrality and Algeria's strategy in the field of renewable energies. The study also assesses the production, storage, distribution and future applications of hydrogen, providing an integrated maintenance plan based on AI technologies to ensure the station's sustainable and efficient operation. This study presents a realistic model of a hydrogen station adapted to Algerian conditions, establishing it as a valuable resource for researchers and decision-makers in this promising field.

Keywords:

Green hydrogen, Hydrogen station, Renewable energy, Solar power, Wind energy, Electrolysis, Alkaline electrolyser, Hydrogen storage, Hydrogen distribution, Functional analysis, FAST diagram, SADT method, 3D design, SolidWorks, Smart maintenance, Artificial intelligence, Predictive maintenance, Energy transition, Algeria

Résumé

L'objectif de cette thèse est de mener une étude exhaustive sur la conception d'une station d'hydrogène vert en Algérie. Cette étude couvrira le cadre théorique de la source d'énergie hydrogène, l'identification des exigences fonctionnelles et de la faisabilité technique, la conception de la station et un plan de maintenance évolutif utilisant les dernières technologies d'intelligence artificielle.

L'étude se concentre sur le potentiel significatif de l'hydrogène dans la transition énergétique mondiale, son rôle dans l'atteinte de la neutralité carbone et la stratégie de l'Algérie dans le domaine des énergies renouvelables. L'étude évalue également la production, le stockage, la distribution et les futures applications de l'hydrogène, fournissant un plan de maintenance intégré basé sur les technologies d'IA pour assurer le fonctionnement durable et efficace de la station. Cette étude présente un modèle réaliste d'une station d'hydrogène adaptée aux conditions algériennes, s'établissant comme une ressource précieuse pour les chercheurs et les décideurs dans ce domaine prometteur.

Mots clés :

Hydrogène vert, Station d'hydrogène, Énergie renouvelable, Énergie solaire, Énergie éolienne, Électrolyse, Électrolyseur alcalin, Stockage d'hydrogène, Distribution d'hydrogène, Analyse fonctionnelle, Diagramme FAST, Méthode SADT, Conception 3D, SolidWorks, Maintenance intelligente, Intelligence artificielle, Maintenance prédictive, Transition énergétique, Algérie

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List of Symbols and Abbreviations

Symbol / Abbreviation	Description
H_2	Hydrogen gas
O_2	Oxygen gas
CO_2	Carbon dioxide
H_2O	Water
NH_3	Ammonia
$NaBH_4$	Sodium borohydride
$NaBO_2$	Sodium borate
C_7H_{14}	Methylcyclohexane
C_7H_8	Toluene
kWh	Kilowatt-hour
kWh/day	Kilowatt-hours per day
MWh	Megawatt-hour
MW	Megawatt
Nm^3	Normal cubic meter – standard volume unit for gases
Bar	Pressure unit (1 bar = 100,000 Pa)
°C	Degrees Celsius
K	Kelvin
wt%	Weight percentage
ΔH	Enthalpy change (heat content variation)
H	Efficiency
pH	Acidity/alkalinity level
Tdehyd	Dehydrogenation temperature
Tboil	Boiling temperature
STP	Standard Temperature and Pressure
SMR	Steam Methane Reforming
ATR	Autothermal Reforming
POX	Partial Oxidation
CCUS	Carbon Capture, Utilization, and Storage
PEM	Proton Exchange Membrane
SOEC	Solid Oxide Electrolyser Cell

PEC	Photoelectrochemical Cell
PV	Photovoltaic
LOHC	Liquid Organic Hydrogen Carrier
HRS	Hydrogen Refuelling Station
MEGC	Multiple-Element Gas Container
UAV	Unmanned Aerial Vehicle
EV	Electric Vehicle
HFCEV	Hydrogen Fuel Cell Electric Vehicle
JSA	Job Safety Analysis
ISO 14687	Hydrogen purity standard for fuel cells
ISO 16111	Standard for hydrogen storage in portable containers
ATEX	Safety standard for explosive atmospheres
NFPA	National Fire Protection Association Standards
SAE J2601	Hydrogen vehicle fueling protocol (pressure and timing)
SAE J2719	Hydrogen fuel quality standard
CSA HGV 4.9	Standard for hydrogen stations for light-duty vehicles
OSHA 1910.147	Occupational safety lockout/tagout regulation
FP	Functional Performance
FC	Functional Constraint
FPI	Functional Primary Interface
A-0 / A0	SADT analysis levels
SADT	Structured Analysis and Design Technique
FAST	Function Analysis System Technique
IoT	Internet of Things
AI	Artificial Intelligence
LLM	Large Language Model
ML	Machine Learning
24/7 Monitoring	Continuous around-the-clock monitoring
LOTO	Lock Out Tag Out – safety isolation method
DOT	U.S. Department of Transportation standards

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General Introduction

In light of escalating global energy crises, growing environmental concerns related to climate change, and emerging international trends toward decarbonization, hydrogen has become a central element of future solutions as a clean and flexible energy source. Green hydrogen, produced from renewable sources, is considered one of the key pillars of the global energy transition. Algeria, endowed with significant renewable energy potential, holds promising prospects to become a major player in hydrogen production and distribution.

This thesis is divided into five interconnected chapters that cover the theoretical, technical, and functional aspects related to the design and maintenance of a green hydrogen station in Algeria.

Chapter One provides a comprehensive overview of hydrogen as an energy source, starting with its historical background and its physical and chemical properties, leading to its role in achieving carbon neutrality. It also addresses global policies supporting hydrogen, the different types of hydrogen, methods of production, storage, and transportation, in addition to future applications. The chapter concludes with a review of hydrogen refuelling stations around the world and Algeria’s vision in this field.

Chapter Two focuses on defining the functional requirements of a future hydrogen station in Algeria by presenting the strategic context and project objectives, then clarifying technical and aesthetic functions. This chapter employs functional analysis tools such as the “Bête à Cornes”, “Pieuvre,” “FAST,” and “SADT” diagrams to identify system interactions, requirements, and constraints.

Chapter Three presents a technical feasibility study, including demand analysis, optimal site selection, and production calculations under various operational scenarios. It also outlines the renewable energy technologies to be used, such as solar panels and wind turbines, in addition to other technical components like electrolysers, compressors, coolers, and dispensers. The chapter also covers the station's integration with the electrical grid and environmental considerations.

Chapter Four addresses the design of the station, which is expected to translate technical and functional requirements into an actual design layout, taking into account the distribution and integration of components.

Chapter Five explores maintenance in the era of artificial intelligence, analysing the shift from traditional maintenance practices to predictive maintenance powered by AI, robotic inspection, and generative AI support for technicians. It also provides a detailed maintenance plan for each major station component, such as solar panels, wind turbines, batteries, electrolysers, compressors, and dispensers.

This thesis offers a comprehensive and multi-dimensional vision for establishing a green hydrogen station in Algeria, grounded in rigorous scientific principles, integrated engineering analysis, and modern technologies that support sustainability.

Chapter 01:

Hydrogen as a Source of Energy

1. Introduction :

Amidst the environmental and economic challenges facing the world today, hydrogen emerges as one of the most promising solutions for transitioning to sustainable, emission-free energy systems. With its unique properties and ability to integrate with renewable energy sources, hydrogen plays a pivotal role in strategies to reduce carbon emissions and enhance energy security. This chapter explores hydrogen’s role as an energy source by delving into its historical roots, its potential in achieving carbon neutrality, and the global policies supporting its adoption. It also examines hydrogen’s physical and chemical properties, its types and production methods, as well as the challenges associated with its storage and transportation. Additionally, the chapter discusses hydrogen’s diverse applications in the energy sector, focusing on the design of hydrogen stations and their implementation conditions particularly in the Algerian context, which seeks to localize this technology as part of its ambitious vision for clean energy. This chapter provides a comprehensive framework for understanding hydrogen as a strategic energy resource for the present and future.

2. Historical Overview of Hydrogen Utilization :

Hydrogen was first identified by the British scientist Henry Cavendish in 1766 when he reacted zinc with hydrochloric acid and later demonstrated that it could produce water. In 1783, French physicist Jacques Charles made the first hydrogen balloon flight. The name "hydrogen" was given by Antoine Lavoisier in 1788. In 1800, two English scientists discovered that an electric current could split water into hydrogen and oxygen by electrolysis. This led to Christian Schoenbein's discovery of the fuel cell effect in 1839, which was further demonstrated by Sir William Grove in 1845. [1]

In the 1920s, Rudolf Erren converted engines to run on hydrogen, while J B S Haldane proposed the idea of renewable hydrogen. The Hindenburg disaster in 1937 highlighted the dangers of hydrogen. In 1958, NASA was founded, using liquid hydrogen for rocket propulsion. The following year, Francis T. Bacon created a practical hydrogen fuel cell to power various applications, including space missions. [1]

In the 1970s, the concept of a hydrogen economy gained traction, especially after the OPEC oil embargo. The National Hydrogen Association was formed in 1989, and the first solar-powered hydrogen plant became operational in 1990. The following years saw the development of various fuel cell vehicles and significant government support for hydrogen research. [1]

By the early 2000s, leading automotive companies were collaborating on hydrogen technologies. Notable initiatives included a $1.2 billion hydrogen fuel initiative announced by President Bush in 2003 and the creation of the International Partnership for the Hydrogen Economy. Hydrogen's journey has included milestones in research, technology and the quest for a sustainable energy future. [1]

3. Hydrogen’s Potential in Achieving Carbon Neutrality :

The worsening climate change emphasizes the very critical worldwide need of reducing greenhouse gases, especially carbon dioxide (CO_2) produced by uncontrolled use of fossil fuels and deforestation. Increasing world temperatures (°C) have worsened extreme weather events, disturbed ecosystems, and endangered human existence, agriculture, coastal zones, water resources, public health, biodiversity, and economic stability by accelerating the hydrological cycle. The 2015 Paris Agreement calls for a fast change in direction toward renewable and low-carbon energy systems to reduce the negative effects on the environment. With versatility across industries from transportation and manufacturing to power generation, hydrogen provides excellent energy density, clean combustion (generating just water vapor), and therefore becomes a vital energy vector in this transformation. Renewable sourced hydrogen is absolutely essential since it supports carbon neutrality objectives, improves energy storage, grid resilience, and decarbonization in difficult-to-abate sectors, thereby placing it as the foundation of sustainable energy policies. [2]

4. Global Policies and Initiatives Promoting Hydrogen Adoption :

Many countries, including 25 nations and the European Commission, are developing policies to support hydrogen development. Australia's goals include shifting from grey to green hydrogen, reducing production costs to below $2 per kilogram, and becoming a major player in global trade by 2030. Brazil aims to strengthen its hydrogen market while focusing on low-carbon goals and international technology cooperation. The European Union is seeking to reduce dependence on Russian fossil fuels by diversifying energy sources and building green hydrogen electrolysers. [3]

Germany is working to develop its hydrogen technology market, improve distribution and transport systems, and increase international cooperation. Japan is developing a market for hydrogen-powered electric vehicles and aims to reduce the cost of blue hydrogen and electrolysis systems. The US is targeting net-zero emissions, cost reduction for fuel cell systems and electrolysers, and job creation with significant revenue generation. [3]

Countries are moving from grey to green hydrogen, with Australia, Brazil and China leading the way. China is investing in electrolyser research, while Japan is developing low-emission hydrogen import channels and promoting fuel cell vehicles. The US is working to reduce costs and overcome export challenges, and the EU is increasing green hydrogen to achieve energy independence from Russia. [3]

5. Physical and Chemical Properties of Hydrogen :

Hydrogen makes up 75% of the visible matter in stars and galaxies, making it the most abundant element in the Universe. It has a simple structure, with a nucleus containing a proton and an electron, which exist in a 'probability cloud' around it. There are three isotopes of hydrogen: Protium (the most common, with one proton), Deuterium (a rare type with one proton and one neutron) and Tritium (unstable and radioactive, with one proton and two neutrons). [4]

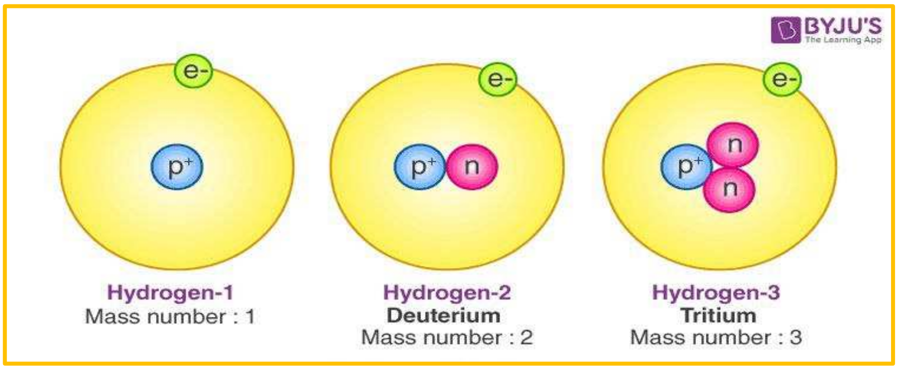


Figure (I-01): Isotopes of Hydrogen [5]

5.1. Physical Properties:

Hydrogen has very low melting and boiling points, making it a cryogenic liquid at normal pressure. Storage as a gas requires high pressure (up to 250 bar), while storage as a liquid requires very low temperatures (below 20 K). However, its low density limits its storage efficiency compared to traditional fuels such as petrol. As pressure increases, so do boiling points, which affects liquefaction efficiency. [4]

Hydrogen is tasteless, colourless and odourless, making leak detection difficult without special sensors. Adding odorants is not practical as they can damage fuel cells. Although hydrogen is non-toxic, it can displace oxygen in confined spaces, creating a risk of suffocation. Accompanying gases such as carbon monoxide can be dangerous because they bind to haemoglobin much more effectively than oxygen. [4]

Hydrogen has an extremely low density, being 14 times lighter than air. The expansion ratio from liquid to gas is significant. Due to its small molecular size, hydrogen can easily leak and accumulate indoors, creating a risk of asphyxiation or explosion. Proper leak detection and ventilation are essential for safety. [4]

5.2. Chemical Properties:

Hydrogen has remarkable chemical reactivity, particularly in exothermic reactions with oxygen, which release large amounts of energy. Hydrogen can also be produced from water by electrolysis. When burned, hydrogen produces no harmful pollutants, making it an excellent fuel for reducing pollution; it can reduce carbon monoxide emissions by 70% and nitrogen oxides by 41%. Fuel cells emit no pollutants, even at low temperatures. [4]

In terms of energy content, hydrogen has a higher calorific value of 141. 86 kJ/g and a lower calorific value of 119. 93 kJ/g, which is more relevant for applications. Its energy density is low in gaseous form, but much higher under pressure or when stored as a liquid. [4]

Hydrogen is highly flammable, with a wide range of flammability and low ignition energy, making it a fire hazard. It burns rapidly and is difficult to detect in daylight. Hydrogen can cause material degradation, particularly in metals due to hydrogen embrittlement. To combat this, it's advisable to use strong materials and avoid micro cracks in storage and piping systems. [4]

6. Types of Hydrogen and Production Methods :

6.1. The Three Primary Types of Hydrogen:

Hydrogen's potential as a clean energy source hinges on its production process. Classified by colours codes, the three predominant types are:

a) Grey Hydrogen:

Grey hydrogen is mostly generated using "steam methane reforming (SMR)," a method that uses natural gas or other fossil fuels as both raw materials and energy supply. It currently leads the world's hydrogen production. The substantial reliance of this technique on carbon-heavy resources leads to significant emissions of CO_2 and greenhouse gases. Emphasizing its considerable environmental impact, hydrogen production is responsible for more than 830 million tonnes of CO_2 emissions every year. Grey hydrogen, the most prevalent but environmentally damaging form of hydrogen, stresses the urgent need of moving towards cleaner alternatives such green hydrogen to lessen the impact of the environment. [6]

- **Grey Hydrogen Subtypes [7]:**
  - **Black Hydrogen:** Produced via coal gasification using black coal.
  - **Brown Hydrogen:** Derived similarly but uses lignite (brown coal). Both subtypes fall under "grey hydrogen," which relies on fossil fuels without carbon capture.

b) Blue hydrogen:

Utilizing carbon capture and storage (CCS) or carbon capture and utilisation (CCU) technology to minimize its environmental impact, blue hydrogen offers a low-emission alternative to grey hydrogen. Including CCS/CCU into the hydrogen production process allows some of the created carbon dioxide emissions to be either permanently stored or put for industrial applications. Still, the performance of these systems varies greatly from project to project: capture efficiencies can range from less than 50% in some cases to more than 90% in more advanced applications, emphasizing the ongoing difficulties in achieving consistent decarbonization results. [6]

c) Green Hydrogen: The Sustainable Frontier

Renewable energy sources such solar, wind, and hydro generate green hydrogen, the sole low-carbon hydrogen type produced alone by "electrolysis." This approach splits water into hydrogen and oxygen, therefore allowing green hydrogen to become the standard for green energy changes by eliminating no CO_2 emissions. Green hydrogen accounts for less than 1% of the overall hydrogen production, notwithstanding its promise. Main cost: As of 2021, three to five times more expensive than grey hydrogen (obtained from fossil fuels) and twice as costly as blue hydrogen (which contains carbon capture). The substantial expenditures come from those related with electrolysis technology and renewable energy infrastructure. [6]

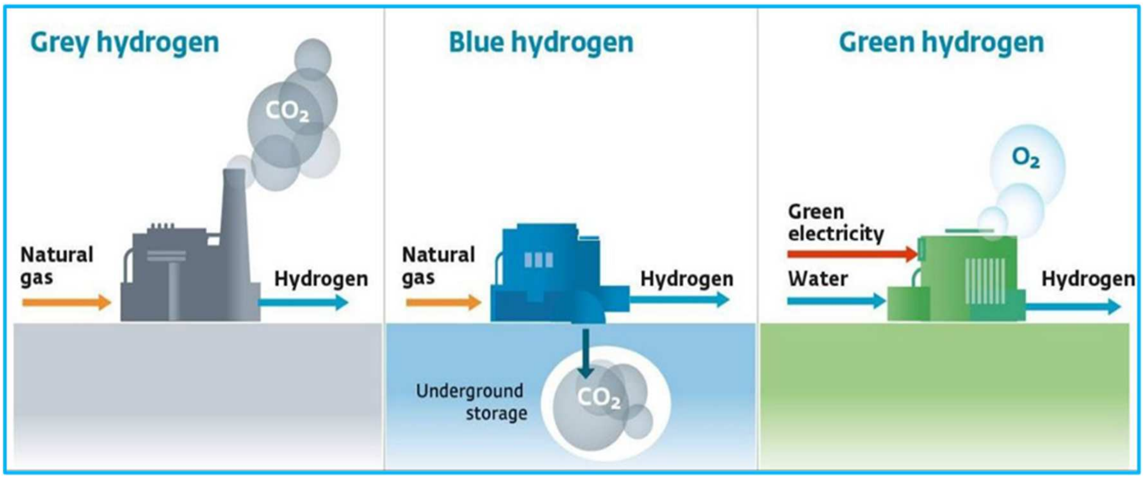


Figure (I-02): Illustration of the three primary methods for Producing Hydrogen [7]

6.2. Other Colours:

a) **Red Hydrogen:** Produced via biomass gasification. Emissions depend on feedstock as well as carbon capture. Fully carbon neutral status can coincide with green hydrogen might. [7]

b) **Pink Hydrogen:** Produced through electrolysis using nuclear power. Often associated with green hydrogen because of zero operational CO_2 emissions, considered low carbon. [7]

c) **Yellow Hydrogen:** Ambiguously refers to solar-power electrolysis hydrogen or grid electricity (a mix of renewable and fossil fuel sources). [7]

d) **Turquoise Hydrogen:** splitting methane into hydrogen and solid carbon using methane pyrolysis. The possibility of a low emission alternative relies on using renewable energy for heat and on carbon storage/use. Not yet validated on a large basis. [7]

e) **White Hydrogen:** Geologically occurring hydrogen naturally present below ground. Presently not economically profitable, this calls artificial manufacturing techniques for industrial usage. [7]

6.3. Hydrogen Production Methods:

a) Hydrogen from Fossil Fuels:

Hydrogen can be generated from various fossil fuels like natural gas and coal, and the intricacy of the processes differs. Because carbon dioxide is generated as a by-product, it is essential to capture the carbon dioxide to guarantee a sustainable (zero emission) process. The practicality of the processes varies for centralized or distributed production facilities. [8]

- **Production from natural gas:**

Hydrogen can be produced from natural gas by three main methods:

The first is Steam Methane Reforming (SMR). In this process, methane and water vapour react to produce hydrogen and carbon monoxide, typically at high temperatures of 700 to 850°C and pressures of 3 to 25bar. Heat is often supplied by burning some of the methane. The resulting gas contains about 12%

carbon monoxide, which can be converted to carbon dioxide and more hydrogen by an additional reaction. [8]

The second method is called partial oxidation (POX). This involves partially burning methane with oxygen gas, producing carbon monoxide and hydrogen. This method produces heat naturally, so it doesn't require external heating. The carbon monoxide produced can also be converted to hydrogen in a later reaction. [8]

The third method is autothermal reforming (ATR), which combines both steam reforming and partial oxidation. This process is exothermic, i.e. it releases heat, and operates at high temperatures (950 to 1100 °C) and pressures up to 100 bar. However, cleaning the output gases can increase costs and reduce overall efficiency. [8]

- **Production from Coal**

Hydrogen can be produced from coal using various gasification methods, such as fixed bed, fluidised bed or high temperature entrained flow. The high-temperature method is preferred because it reduces the production of unwanted by-products such as char, tars and phenols. The process uses heat to convert carbon into carbon monoxide and hydrogen. As this reaction requires heat, similar to methane reforming, it's essential to provide extra energy. The carbon monoxide is then converted into carbon dioxide and hydrogen in another reaction. Producing hydrogen from coal is more complex and costly than from natural gas, but it is still commercially viable. Given the world's abundance of coal, it makes sense to research cleaner technologies for its use. [8]

b) Hydrogen from Splitting of Water:

Hydrogen can be produced by splitting water using various processes such as water electrolysis, photo-electrolysis, photobiological production and high-temperature water splitting. [8]

- **Water electrolysis:**

Water electrolysis refers to the method of dividing water into hydrogen and oxygen through the application of electrical energy, as represented in equation (1). The overall energy needed for water electrolysis experiences a slight rise with an increase in temperature, whereas the electrical energy needed diminishes. Consequently, a high-temperature electrolysis method may be more advantageous if elevated temperature heat is accessible as waste heat from different processes. This holds particular significance on a global scale since the majority of electricity production relies on fossil fuels that exhibit comparatively low efficiency. [8]

$$H_2O + \text{electricity} \rightarrow H_2 + {}^{1}/_{2}\, O_2 \quad (1)$$

- **Alkaline electrolysis:**

Alkaline electrolysis uses a liquid KOH solution as the electrolyte, which is circulated through electrolysis cells. This technology is well developed and works well for stationary applications at pressures up to 25 bar. The main reactions are the conversion of water to hydrogen and oxygen. Alkaline electrolysers typically consist of several cells organised in a stack. Future research aims to reduce costs and improve energy efficiency. [8]

- **Polymer electrolyte membrane (PEM) electrolysis:**

Polymer electrolyte membrane (PEM) electrolysis does not require a liquid electrolyte, making it simpler in design. Instead, it uses an acidic polymer membrane and can operate at high pressures, making it suitable for both stationary and mobile applications. However, PEM systems have limitations such as shorter membrane life and higher costs compared to alkaline systems. They offer advantages such as improved safety, a higher turndown ratio and a more compact design. [8]

- **High Temperature electrolysis:**

High temperature electrolysis operates at temperatures around 1000°C, which reduces electrical energy consumption compared to lower temperatures. The solid oxide electrolyser cell (SOEC) operates in the 700 to 1000°C range, allowing reversible reactions. Current efforts focus on using heat from geothermal, solar or natural gas sources to improve efficiency, while challenges include materials development and stress management in ceramic components. [8]

- **Photo electrolysis (photolysis):**

Photovoltaic (PV) electrolysers, which use solar panels and electrolysers to produce electricity or hydrogen, have efficiency problems due to their two-step process. In contrast, direct photo-electrolysis (PEC) combines light absorption and water splitting in a single device, potentially reducing costs and simplifying hydrogen production. An international research effort involving more than 13 OECD countries, led by the IEA-HIA, is focusing on four PEC designs: tandem systems, monolithic multi-junction devices, dual-bed redox systems and one-pot two-step systems. While laboratory PEC devices have achieved solar-to-hydrogen efficiencies of 16%, commercial success depends on overcoming key challenges. These include developing durable photoelectrode materials, optimising semiconductor properties and improving surface chemistry. In addition, engineering issues such as current matching, resistance reduction and safe gas management need to be addressed. While PV electrolysis currently dominates, PEC technology could transform sustainable hydrogen production if materials, scalability and engineering challenges are addressed through collaborative innovation. [8]

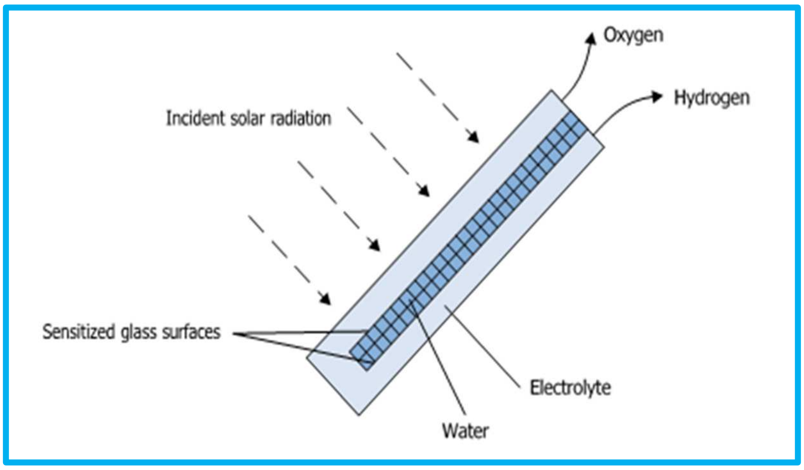


Figure (I-03): Photo-electrolysis working principle [8]

- **Photobiological Production (Bio photolysis):**

The generation of hydrogen through photosynthesis (2) followed by catalysis via hydrogenases (3) in green algae and cyanobacteria forms the foundation for photo biological hydrogen production. The need for extensive fundamental and applied research in this sphere is unquestionable, as the successful outcome of such studies could lead to a sustainable solution for renewable hydrogen production. It is crucial to understand the natural mechanisms and the genetic controls involved in H_2 production. Metabolic and genetic manipulation can be applied to scale the process in larger bioreactors, while another alternative is to replicate the two stages through artificial photosynthesis. [8]

$$\text{Photosynthesis: } 2H_2O \rightarrow 4H^+ + 4e^- + O_2 \ (2)$$

$$\text{Hydrogen Production: } 4H^+ + 4e^- \rightarrow 2H_2 \ (3)$$

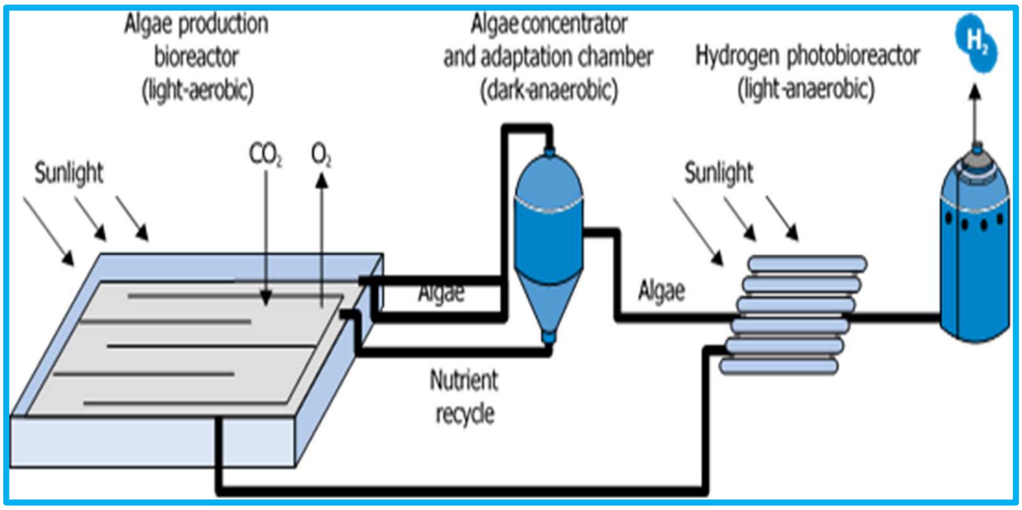


Figure (I-04): Principle of photobiological hydrogen production [8]

- **High temperature splitting of water:**

At around 3000 °C, water can be split into hydrogen and oxygen, which can then be recycled. Several methods have been proposed to achieve this at lower temperatures, including thermos chemical cycles, hybrid systems combining thermal and electrolytic methods using ceramic membranes for separation, and plasma-chemical methods in a two-stage CO_2 cycle. These approaches could achieve efficiencies of over 50% and significantly reduce the cost of hydrogen production. However, challenges remain, such as developing materials that resist corrosion at high temperatures, improving high-temperature membranes and separation processes, and ensuring effective heat exchangers and storage. Design and safety considerations are critical when working at these temperatures. [8]

Thermo chemical water splitting converts water into hydrogen and oxygen through a series of heat-driven chemical reactions. Although this process has been researched for decades, no affordable cycles have yet been developed for commercial use. One example is the iodine/sulphur cycle, but challenges such as handling corrosion-resistant materials could pose serious problems. [8]

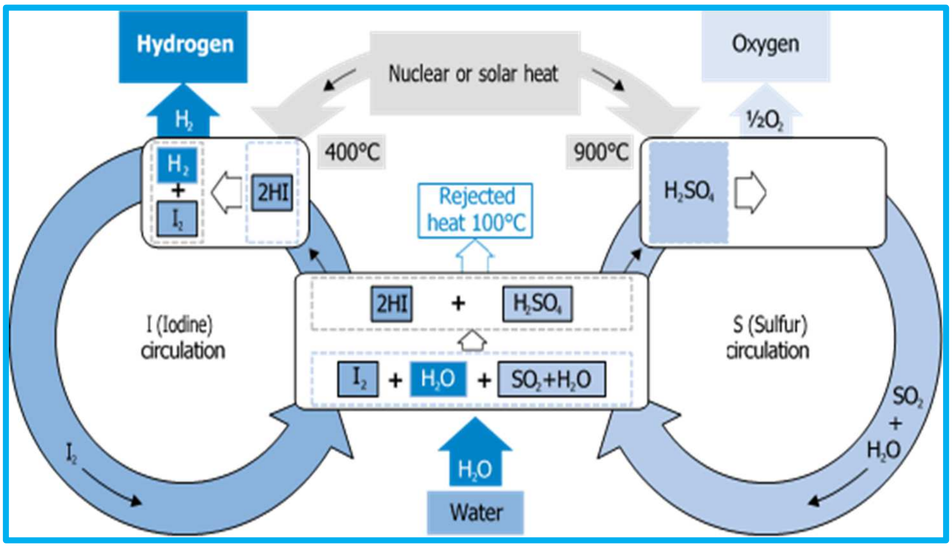


Figure (I-05): This is a simple diagram of the iodine/sulphur thermochemical process [8]

c) Hydrogen from Biomass:

When biomass is converted into energy, the process usually produces a gas containing hydrogen, similar to the gas produced from coal. There are currently no commercial plants that successfully produce hydrogen from biomass. The methods used include steam gasification, entrained-flow gasification and advanced concepts such as supercritical water gasification. However, none of these methods has yet produced hydrogen. Biomass gasification is a key area for both hydrogen and biofuel research. Gasification and pyrolysis appear to be the most promising for hydrogen production in the near future. The process can involve drying the biomass, but this may not be cost effective, so methods using wet biomass are being sought. Biomass feedstocks are of inconsistent quality, influenced by crop type and environmental factors, which makes technological progress difficult. There's a need to standardise quality and production to achieve better fuel consistency. Larger plants can handle lower quality fuels better, while smaller plants require higher quality fuels. Several steps are needed to improve the economics and logistics of biomass feedstock production, including better feedstock preparation, gasification research, raw gas purification and addressing system integration issues. Understanding fuel quality requirements in relation to production scale is essential. [8]

7. Hydrogen Storage and Transportation Systems :

7.1. Hydrogen Storage:

a) Gaseous Hydrogen:

The most common method of storing hydrogen in its gaseous state is in steel tanks, although lightweight composite tanks designed to withstand higher pressures are increasingly being used. Cryogenic gas, which refers to gaseous hydrogen cooled to near cryogenic temperatures, is another option that can increase the volumetric energy density of gaseous hydrogen. A more innovative approach to storing hydrogen gas at high pressure is the use of glass microspheres. [8]

o Composite tanks:

Composite tanks for hydrogen storage are lightweight and commercially available. They meet safety regulations for high pressures and do not need internal heat exchange. However, they have some drawbacks, including their large size, high cost, energy losses from gas compression, and safety concerns about hydrogen loss during accidents. There is a need for more research in areas such as exploring material embrittlement, developing stronger and cheaper materials, and creating an efficient oil-free compressor for 1000 bar pressures.[8]

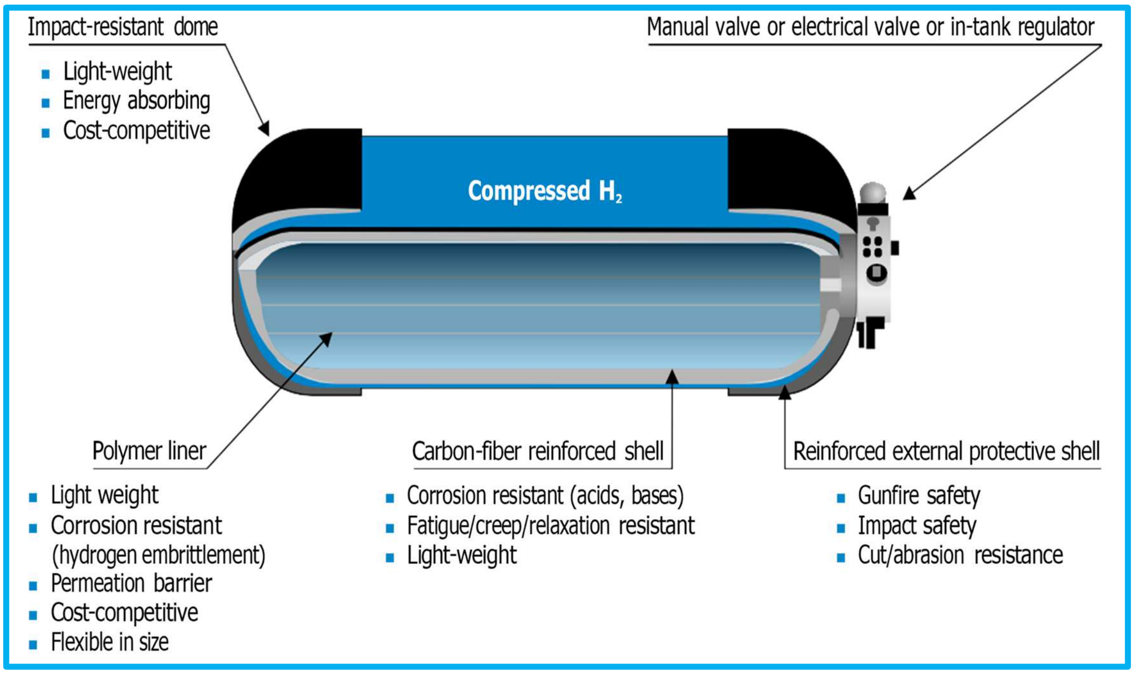


Figure (I-06): Diagram of a typical compressed H_2 gas tank (Quantum Technologies) [8]

o Glass microspheres:

Glass microspheres can be used to store hydrogen gas for vehicles in three steps: loading, filling and discharging. First, hollow glass spheres are filled with hydrogen at high pressure (350-700 bar) and high temperature (around 300 °C). Once cooled to room temperature, they are transferred to the vehicle's tank. To release the hydrogen for use, the spheres are heated to around 200-300°C. [8]

Challenges with this method include low storage density, slow hydrogen leakage at normal temperatures, fragility during use and the need for high heating temperatures above normal fuel cell temperatures (70-80°C). However, glass microspheres are safe because they store hydrogen at lower pressures and can be formed into adaptable tanks, helping to reduce container costs. They have a storage density of 5. 4 wt% H_2. Current research aims to reduce release temperatures to below 100 °C and focuses on creating stronger glasses, finding low-cost production methods, optimising hydrogen permeability and developing non-thermal control techniques. [8]

b) Liquid Hydrogen:

The most common way to store hydrogen in liquid form is to cool it to cryogenic temperatures (-253°C). Other options include storing hydrogen as a component of other liquids, such as $NaBH_4$ solutions, rechargeable organic liquids or anhydrous ammonia NH_3. [8]

o Cryogenic Liquid Hydrogen (LH_2):

Cryogenic hydrogen, known as liquid hydrogen (LH_2), has a density of 70. 8 kg/m3 at its boiling point of -253°C. While its theoretical gravimetric density is 100%, practical systems can only achieve 20% by weight. On a volumetric basis, LH_2 offers a better energy density than compressed gas, but loses 30-40% of its energy during production. Liquid hydrogen also faces challenges such as boil-off losses during storage and requires super-insulated containers. Public perception often sees LH_2 as unsafe. The main advantage of LH_2 is its high storage density at low pressure, making it suitable for commercial vehicles and potential aviation fuel. Key research challenges include improving liquefaction processes, reducing container costs, and developing systems to capture and re-liquefy boil-off. [8]

o $NaBH_4$ solutions:

Borohydride ($NaBH_4$) solutions can be used as a liquid storage medium for hydrogen. The catalytic hydrolysis reaction is as follows [8]:

$$NaBH_4\,(l) + 2H_2O\,(l) \rightarrow 4H^2\,(g) + NaBO_2\,(s)\ \text{(ideal reaction)}\ (1)$$

The theoretical maximum hydrogen energy storage density for this reaction is 10.9 wt% H_2, the ideal reaction is $4H_2/\,(NaBH_4 + 2H_2O)$. The specific cost (USD/kg) of hydrogen storage using $NaBH_4$ solutions is easy to calculate [8]: Cost of H_2 = 4.69 × Cost of $NaBH_4$ (ideal reaction) (2)

The main advantage of using $NaBH_4$ solutions is the safe and controllable production of hydrogen (H_2) on board. However, a major disadvantage is that $NaBO_2$, the reaction product, has to be converted back to $NaBH_4$ off-board. At present, regenerating $NaBH_4$ is expensive, costing around \$50/kg, and needs to fall below \$1/kg, which seems unlikely. However, some companies, such as Millennium Cell and MERIT, are supporting this technology. $NaBH_4$ solutions could be practical for high value portable and stationary applications. Research and development challenges identified include optimising water usage in reactions for ideal energy density, finding methods for $NaBO_2$ removal and regeneration, and developing a direct borohydride fuel cell. [8]

- **Rechargeable organic liquids:**

Some organic liquids can store hydrogen in liquid form. The process consists of three main steps. First, an organic liquid is converted to H_2 gas using a catalyst. Second, the gas is transported to a processing plant while fresh H_2 rich liquid is returned to the vehicle. Finally, the depleted liquid is converted back to its original state and returned to the fuelling station. [8]

An example of a rechargeable organic liquid process is the dehydrogenation and hydrogenation of methylcyclohexane (C_7H_{14}) and toluene (C_7H_8) [8]:

$$C_7H_{14}\ (l) \leftrightarrow C_7H_8\ (l) + 3\ H_2\ (g)\ (T_{dehyd} = 300\text{-}400\ °C)\ (3)$$

The ideal reaction mentioned above offers a hydrogen energy storage density of 6.1 wt% and 43 kg H_2/m3. Careful handling of organic liquids such as methylcyclohexane is essential, as they react dangerously with strong oxidants, creating fire hazards. Safety and toxicity studies are essential. Research should also assess potential infrastructure and costs. Key challenges include developing organic systems for low temperature dehydrogenation, creating effective metal catalysts and improving the re-hydrogenation process. Liquid hydrogen needs a well-organised infrastructure for safety, and needs to be widely available to reduce transport costs and to serve applications beyond vehicles, such as power generation and aviation. Borohydride solutions and organic liquids may be better for refuelling land transport. [8]

c) Solid Hydrogen:

Storage of hydrogen in solid materials has the potential to become a safe and efficient method of energy storage for both stationary and mobile applications. There are four main groups of suitable materials: carbon and other high surface area materials; H_2O reactive chemical hydrides; thermal chemical hydrides; and rechargeable hydrides. [8]

- **Carbon and other high surface area materials:**

Carbon based materials such as nanotubes and graphite nano fibres have been extensively researched, but earlier claims of high hydrogen storage capacities (30-60 wt%) are now considered to be inaccurate. Current capacities are limited to about 6 wt% at cryogenic temperatures, with higher temperatures required for atomic hydrogen adsorption. Research should focus on understanding surface properties, exploring new binding mechanisms and developing carbon-metal composites. Other materials such as zeolites, MOFs and clathrate hydrates also show potential but require further investigation for room temperature applications. [8]

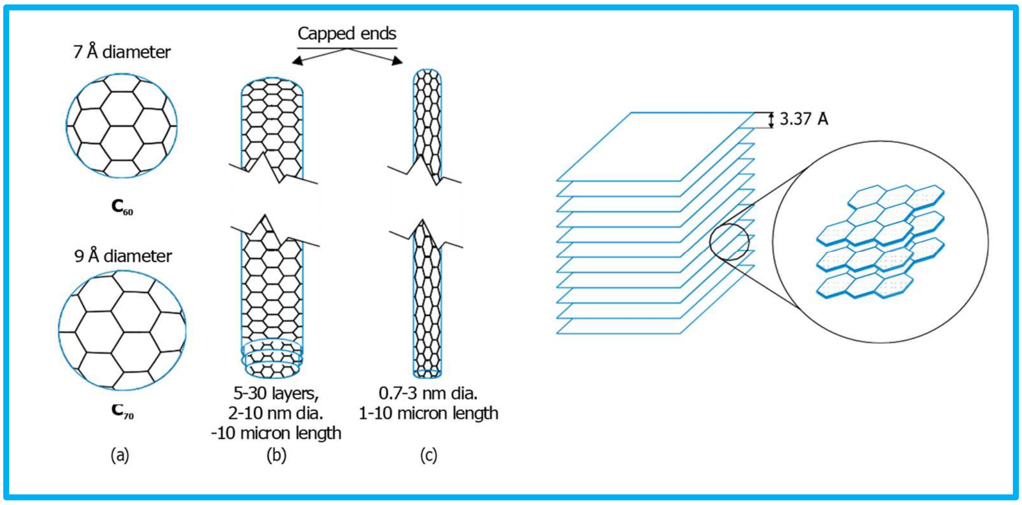


Figure (I-07): Schematic of (a) fullerene carbons buckyballs, (b) multi wall nanotubes (MWNT), (c) single-wall nanotubes (SWNT) [8]

- **Rechargeable hydrides:**

Rechargeable metal hydrides such as $NaAlH_4$ and $LiBH_4$ have been studied for years. $NaAlH_4$, when catalysed, shows improved performance but only achieves 4-5% reversible hydrogen weight, falling short of targets. Borohydrides such as $LiBH_4$ offer higher capacities and stability, but require further research to improve reversibility, reduce desorption temperatures and lower costs. [8]

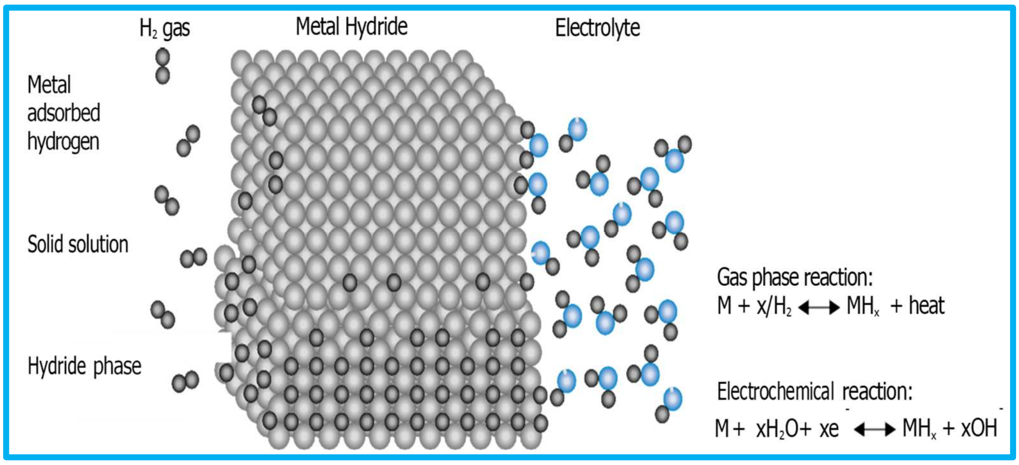


Figure (I-08): Diagram of a rechargeable metal hydride battery [8]

- **Chemical hydrides (H_2O reactive):**

These hydrides, such as NaH and MgH_2, can be managed in semi-liquid forms and produce hydrogen through hydrolysis reactions. MgH_2 offers a good balance between hydrogen yield and cost, but the energy-intensive regeneration of spent hydroxides remains a challenge for vehicle applications. [8]

- **Chemical hydrides (thermal):**

Ammonia borane is a solid hydrogen storage material that decomposes in several steps to release hydrogen. However, the process is irreversible and produces toxic gases. Research is aimed at reducing decomposition temperatures, developing safe on-board systems and developing cost-effective off-board regeneration methods. [8]

7.2. Transportation Systems:

To establish clean hydrogen supply chains and exploit the low-cost opportunities in remote areas, there is an immediate need for practical, large-scale clean hydrogen transport solutions. Four hydrogen transport technologies are the most promising: pipelines carrying gaseous hydrogen; hydrogen delivered as ammonia; liquefied hydrogen (LH_2); and hydrogen contained in liquid organic hydrogen carriers (LOHC). [9]

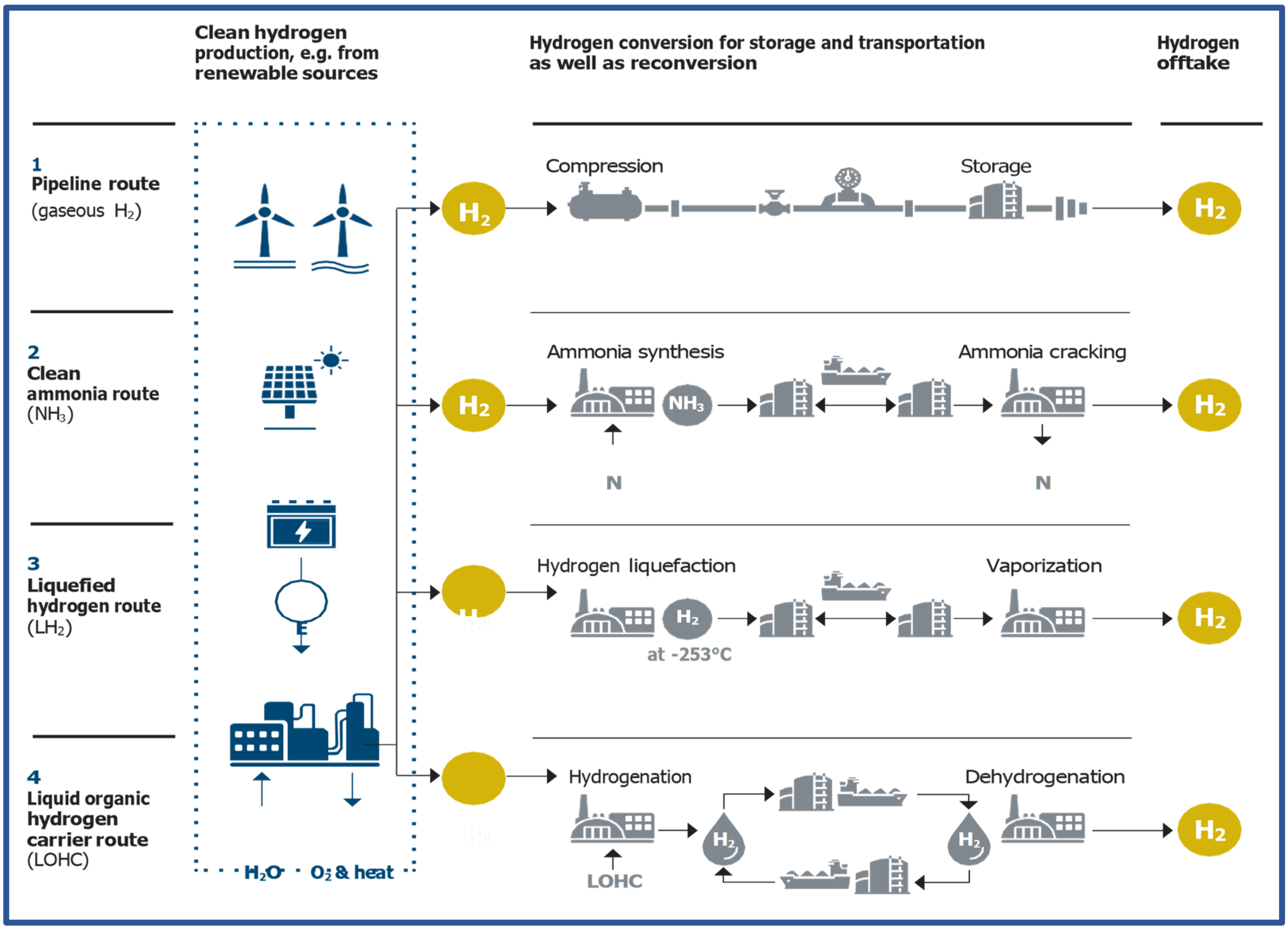


Figure (I-09): The most common routes for large scale hydrogen transport [9]

a) Pipelines (Gaseous H_2):

Gaseous hydrogen can be transported through pipelines in a similar way to natural gas. The hydrogen is compressed before it enters the pipeline, and in some cases needs to be recompressed at various points along the way. Storage facilities are also needed to manage fluctuations in supply. A proper pipeline system requires metering stations, control valves and gates for flow management. [9]

Existing natural gas pipelines can be adapted to transport hydrogen, with trials testing blends of up to 20% hydrogen in gas networks. Hydrogen pipelines have low operating costs, long life and have been successfully operated over thousands of kilometres in Europe and the USA. They can also be used for storage, providing a reliable supply to users. In addition, the use of pipelines can have a lower environmental impact than multiple power cables. [9]

However, building new pipelines has high initial costs and long construction times, often over ten years. Permitting and cooperation for cross-border projects can also complicate the process. A significant amount of hydrogen is required to make pipelines efficient, and not all consumers are located along pipeline routes, which may require additional infrastructure investment. There are regulatory uncertainties regarding natural monopolies and the integration of these pipelines with existing natural gas systems. There are concerns about the compatibility of old pipelines with hydrogen. [9]

While pipelines are critical for delivering large volumes of hydrogen, they may not be able to meet the demand of widely dispersed large consumers or support future import routes into the EU. More flexible hydrogen transport solutions will be needed to supply users not close to pipelines, leading to a focus on hydrogen carriers for long-distance transport. [9]

b) Ammonia:

Ammonia (NH3) is mainly produced from natural gas and is widely used in fertiliser production. It can also be used as a clean hydrogen storage method. Ammonia is produced by combining hydrogen and nitrogen from the air in a process similar to the traditional Haber-Bosch process. The liquid ammonia is transported in refrigerated tanks and later separated into nitrogen and hydrogen at its destination. Although ammonia is often transported, most of it is still produced close to where it is used. [9]

The advantages of ammonia synthesis include its established production process, which can be adapted for clean hydrogen. Historical production relied on hydrogen produced from hydroelectric power until cheaper natural gas became the standard. The existing infrastructure for storing and transporting ammonia is well developed, and liquid ammonia holds more hydrogen by volume than other carriers. [9]

But there are drawbacks. Ammonia is toxic and can cause air pollution, affecting human health and environmental quality. This toxicity may limit its use outside large-scale industry, and safety concerns may limit transport in populated areas. In addition, integrating renewable hydrogen into existing plants is difficult, and both the production and cracking processes are energy-intensive and still at an early stage of development, requiring improvements to make hydrogen usable. [9]

c) Liquefied Hydrogen (LH_2):

The storage density of hydrogen can be improved by cooling it to below minus 253°C, which turns it into liquid hydrogen (LH_2). After this process, LH_2 is stored in insulated tanks to prevent heat transfer and evaporation, and any gas that builds up must be vented. LH_2 can be transported in specially designed trailer trucks and is vaporised back to gas for use at its destination. [9]

Liquefaction is a well-known technology that provides high purity hydrogen and is currently used in areas such as aerospace and petrol stations. However, it uses a lot of energy and is more complicated to store and transport than other methods. Long-term storage can result in losses, and large-scale transport is still being developed, resulting in high costs. Overall, the infrastructure for LH_2 is more expensive than for other hydrogen carriers. [9]

d) Liquid Organic Hydrogen Carriers (LOHC):

Liquid Organic Hydrogen Carriers (LOHC) are compounds that can hold and release hydrogen for transport. Hydrogen is chemically bound to the liquid for transport at normal pressure and can be released at the destination by a process requiring heat. This allows the LOHC to be reused after dehydrogenation. Benzyl toluene, a common organic carrier, is highlighted for its advantages. [9]

Benzyl toluene's advantages include safe storage and transport, good viscosity at different temperatures and compatibility with existing infrastructure. It allows long storage times without hydrogen losses and can effectively manage fluctuating hydrogen supplies from renewable sources. [9]

Disadvantages include the need for high temperatures during dehydrogenation, which increases energy costs. In addition, large quantities of LOHC are required for hydrogen transport, which increases capital costs and production requirements. The production process also increases CO_2 emissions, and the long-term effectiveness of LOHC in real-world environments has yet to be fully confirmed, although early projects show promise. [9]

8. Applications of Hydrogen in the Energy Sector :

Hydrogen fuel cells have several practical applications that improve efficiency and reduce emissions in a variety of sectors. [10]

In warehouse logistics, many companies are using hydrogen fuel cells to power trucks, forklifts and pallet jacks, improving productivity and air quality in the workplace. For global distribution, hydrogen-powered trucks and vans from companies such as Nikola and UPS can operate efficiently over long distances. [10]

Public transport is also seeing growth with hydrogen fuel cell buses, particularly in Europe, while the US is exploring similar programmes in states such as California and Nevada. In the rail sector, hydrogen fuel cell trains are being tested in countries such as Germany and the UK, while efforts are underway in the US to develop hydrogen-powered locomotives. [10]

Nine major car manufacturers are working on hydrogen fuel cell electric vehicles (HFCEVs) for personal use, with notable models such as the Toyota Mirai and Honda CR-V. In the aerospace sector, experimental projects are exploring hydrogen applications in aircraft, with the aim of commercial flights by 2025. [10]

For back-up power, stationary fuel cells are supporting critical systems, with companies such as Microsoft testing hydrogen back-up generators. Mobile power generation is also gaining traction, with General Motors planning to use hydrogen fuel cells for new mobile generators. [10]

Unmanned aerial vehicles (UAVs) are also benefiting from hydrogen fuel cells, which offer longer range and faster refuelling compared to conventional batteries. Finally, hydrogen fuel cells are being integrated into marine applications, powering boats and submarines, including military vessels that benefit from quiet operation and extended range. [10]

9. Future Trends and Innovations in Hydrogen Technology :

Hydrogen is poised to revolutionize the global energy landscape as a versatile, clean energy carrier, playing a pivotal role in decarbonizing industries, transportation, and energy storage. With accelerating global efforts to achieve net-zero emissions, hydrogen technology is advancing rapidly, driven by policy support, cross sector collaboration, and ground breaking innovations. Below are the key trends and developments shaping its future [11]:

9.1. Global Momentum Toward Hydrogen Adoption:

a) Policy Frameworks [11]:

- The EU’s Hydrogen Strategy aims to deploy 40 GW of electrolysers by 2030, prioritizing green hydrogen to meet climate neutrality by 2050.
- The U.S. is channelling investments via the Infrastructure Investment and Jobs Act and Inflation Reduction Act to scale hydrogen infrastructure and reduce costs.
- MENA nations (e.g., Saudi Arabia, UAE, Oman) are leveraging abundant renewables for mega-projects like NEOM, the world’s largest green hydrogen plant, to position themselves as global hydrogen exporters.

b) International Collaboration [11]:

- Initiatives like the Hydrogen Council and cross-border partnerships (e.g., Australia Japan hydrogen exports) are fostering global supply chains.
- Germany and the UAE are investing billions in infrastructure, including pipelines and ammonia export hubs, to integrate hydrogen into energy systems.

c) Funding and Private Sector Engagement [11]:

- Over $1.5 billion in venture capital flowed into hydrogen start-ups in 2023, signalling strong private-sector confidence.
- Energy giants (Shell, BP, Total Energies) are collaborating with governments to develop green hydrogen clusters.

9.2. Innovations in Hydrogen Production:

a) Green vs Blue Hydrogen [11]:

- **Green Hydrogen:** Produced via electrolysis powered by renewables, it is emission-free but currently costly ($3–6/kg). Advances in electrolyser efficiency and falling renewable energy prices could slash costs by 50% by 2030.
- **Blue Hydrogen:** Relies on natural gas paired with carbon capture (CCUS), but faces scrutiny over methane leaks and CCUS reliability.

b) Electrolyser Breakthroughs [11]:

- **Proton Exchange Membrane (PEM):** Ideal for flexible, small-scale applications due to rapid response times.
- **Solid Oxide Electrolysers (SOE):** High-temperature operation suits industrial uses (e.g., steelmaking) and boosts efficiency.
- R&D is reducing reliance on expensive catalysts (e.g., platinum), lowering costs and improving durability.

c) Scaling Infrastructure [11]:

- Mega-projects in Europe and Australia are driving economies of scale, with electrolyser capacities expanding to gigawatt levels.

10.Hydrogen Station presentation and Implementation conditions :

10.1. Hydrogen Refuelling Stations around the world:

There is a growing push to reduce carbon emissions through cleaner fuels, and hydrogen is seen as a strong alternative to diesel. The benefits of hydrogen include efficient range, fast refuelling and low emissions, making the development of hydrogen refuelling infrastructure important. By early 2024, 1,680 hydrogen refuelling stations (HRS) are planned worldwide, with 1,148 currently in operation. [12]

Many countries are developing HRS, particularly in the Asia-Pacific region, which has the most stations. At the beginning of 2024, 41 countries had operational HRS and 7 more were planning to build them. However, only 10 countries have 92% of these stations, with China, South Korea, Japan and Germany accounting for 72% of the global total. The Asia-Pacific region accounts for 64% of the world's HRS, mainly in China, South Korea and Japan. South Korea has increased its number of stations, while Japan has decreased. More than 20 European countries also have HRS, with Germany leading the way, while the USA and Canada are expanding their networks. Recently opened significant stations in South Korea and France meet the growing demand for hydrogen, with Bulgaria and Singapore opening their first stations in early 2024. [12]

10.2. Hydrogen Station Implementation Conditions:

a) Hydrogen Quality:

Hydrogen dispensed at the station must meet standards set by the Department of Food and Agriculture and follow specific automotive product specifications. It should comply with the latest version of SAE

International J2719 for hydrogen fuel quality and the Compressed Gas Association's guidelines for gaseous and liquid hydrogen. The station must pass a hydrogen purity test before starting operations, every six months after, and whenever there is a risk of contamination. The applicant must implement and describe best practices to maintain hydrogen purity standards. [13]

b) Protocols for Refuelling:

The station and dispenser must comply with SAE International standards for refuelling vehicles and equipment, including the latest version of SAE J2601/2 for heavy duty vehicles. The applicant must explain how the refuelling protocol and equipment meet the requirements of the project vehicle. If a different refuelling protocol is proposed, it must be described in detail and how it meets the requirements of the project vehicles in terms of tank capacity and refuelling pressure. Safety procedures must also be included to ensure safe and reliable refuelling. If the application includes access for non-project light-duty vehicles, it must follow SAE J2601 for those vehicles. [13]

c) Fire safety:

Fire and safety awareness, prioritisation and compliance where practicable and taking into account local regulations, applicants must Comply with the requirements of fire code sections. [13]

d) Pressure of the dispenser:

Dispenser pressure for the hydrogen refuelling station planned for the project, which dispenses gaseous hydrogen into the storage tanks of heavy-duty vehicles, the applicant shall specify the refuelling pressure to be used for refuelling the project vehicles. [13]

e) Requirements for the station design:

Hydrogen refuelling stations must have a back-up plan for refuelling project vehicles if the main station is not available. The applicant must provide a detailed plan, equipment list and performance specifications to demonstrate that they can arrange for temporary refuelling from a qualified supplier. Stations designed for light-duty vehicles, trucks and SUVs up to 14,000 lbs must comply with the CSA HGV 4.9 Hydrogen Refuelling Station Standards. These standards cover the design, installation, operation and maintenance of stationary and modular hydrogen refuelling stations for light-duty vehicles. [13]

11.Hydrogen and Algerian vision :

Algeria aims to be a major player in the global green hydrogen market, using its renewable energy resources to create a clean energy source that will diversify its energy mix, reduce carbon emissions and reduce dependence on fossil fuels. The country plans to produce green hydrogen for both local use and export, and aims to be a leader in renewable energy in the region. Algeria's strategy is part of a broader effort to modernise its energy sector, attract foreign investment and contribute to global climate goals. [14]

The National Strategy 2023 sets goals for the development of a hydrogen sector to increase energy security and support climate commitments. Algeria aims to become a leader in hydrogen production by 2040, producing 30-40 TWh to meet 10% of Europe's needs and creating a robust industrial framework for hydrogen production and use. The production capacity target is to produce 40 TWh of hydrogen by 2040, with 10 TWh for domestic consumption, mainly from solar and wind energy sources. [14]

Key economic impacts include generating $10 billion annually from hydrogen exports by 2040, reducing dependence on fossil fuels, and creating new jobs and industries. Partnerships with countries such as Germany and companies such as Cepsa are being developed to strengthen Algeria's hydrogen infrastructure, supported by an estimated $24.8 billion investment required for production infrastructure. [14]

12.Conclusion :

This chapter ends by stressing hydrogen's absolutely essential function as a critical connection between renewable energy sources and contemporary industrial and mobility requirements. The research clearly shows that hydrogen is not just a good substitute for fossil fuels but rather a keystone of the worldwide energy transition. Examining worldwide policies and technical advancements reveals that creating effective hydrogen infrastructure depends on the coordination of technical, financial, and legal aspects. While providing novel and practical ideas, the chapter also stresses difficulties in erecting hydrogen stations among them storage and transport efficiency that need solved. Regarding Algeria's national vision, the review of natural resources and existing infrastructure shows great possibility to position Algeria as a major player in hydrogen markets worldwide and in the region. In this way, this part gives a theoretical and practical basis for hydrogen station design, driven by a forward-thinking approach in line with worldwide trends toward a low carbon economy.

Chapter 02:

Functional Requirements Document for Algeria's future Green Hydrogen Station

1. Introduction:

Amid the global shift towards a low carbon economy, green hydrogen technology stands out as an encouraging option to improve energy sustainability and reduce dependence on fossil fuels. Algeria, with its extensive renewable energy capacity (especially solar and wind), offers an optimal environment for the development of green hydrogen stations to support its national goals of energy diversification and emission reduction. This chapter presents the Functional Requirements Document (FRD) as a reference framework that describes the essential requirements for creating an integrated green hydrogen station, from hydrogen production through electrolysis using renewable energy to its effective and safe storage and distribution. The FRD is designed to provide engineers, designers and stakeholders with a transparent roadmap that ensures compliance with international standards and responsiveness to local requirements, paving the way for detailed design in later chapters.

2. Strategic Context :

Algeria aims to strengthen its position as a leader in clean energy by adopting innovative projects that support the global energy transition. The green hydrogen station represents a strategic solution to leverage abundant natural resources (solar and wind) and reduce dependence on fossil fuels, aligning with Algeria's commitments to international climate agreements.

3. Project Objectives :

a) **Sustainability :** Produce carbon free green hydrogen using renewable energy.
b) **Economic Diversification :** Create new investment opportunities in the clean energy sector.
c) **Regional Integration :** Supporting sustainable transport by meeting local and regional demand for green hydrogen.

4. System's Main Functions :

4.1. Functional Requirements:

Function	General Description
Renewable Energy Generation	Convert solar and wind energy into clean electricity using advanced technologies.
Providing emergency power supplies	Renewable energy is stored in batteries during peak periods and, in the event of a total power outage, the local electricity grid is resorted to.
Supplying water for the electrolysis process	Providing tanks for deionised water and ensuring that they are refilled regularly.

Hydrogen Production via Electrolysis	Split water molecules using efficient technology to extract high purity hydrogen.
Hydrogen compression and cooling	Ensuring hydrogen pressure is at appropriate levels and cooling it to facilitate storage
Hydrogen storage	Ensuring the safe storage of hydrogen in storage containers under controlled pressures and temperatures.
Hydrogen Distribution to End Users	Provide smart distribution units tailored for light and heavy-duty vehicles.
Safety and Quality Assurance	Continuous process monitoring with leak detection and fire suppression systems.

Table (II-01): Functional requirements for green Hydrogen Station

4.2. Aesthetic and User Centric Functions:

- **Modular Design:** Scalability to meet future demand.
- **User Interaction:** Smart interfaces to streamline refuelling processes.
- **Environmental Responsibility:** Solutions promoting recycling and waste reduction.

5. General Requirements and Constraints :

5.1. Functional Requirements:

- **Energy Sources:** Use high-efficiency solar and wind technologies.
- **Hydrogen Purity:** Ensure compliance with international quality standards.
- **Safe Storage:** Design corrosion resistant, airtight storage tanks.
- **Efficient Distribution:** Provide distribution units compatible with various vehicle types.

5.2. Binding Constraints:

- **Environmental Compliance:** Adherence to emission reduction and waste management standards.
- **Safety:** Implementation of hazard prevention systems in flammable environments.
- **Timeline:** Complete the project within a reasonable timeframe with a regular maintenance schedule.

6. Targeted Performance :

- **Energy Efficiency:** Optimize energy consumption across production stages.
- **Reliability:** Ensure operational continuity under challenging weather conditions.
- **Flexibility:** Ability to adapt to future technological developments, especially artificial intelligence technologies.

7. Integration with the Algerian Context :

- **Optimal Locations:** Select regions with high solar irradiance and suitable wind speeds.
- **Infrastructure:** Leveraging existing infrastructure and projects, such as connecting electricity grids.
- **Local Capacity Building:** Train national personnel to manage and operate the station.

8. Supporting Documentation:(Structural Diagrams)

8.1.Bête à Cornes Diagram:

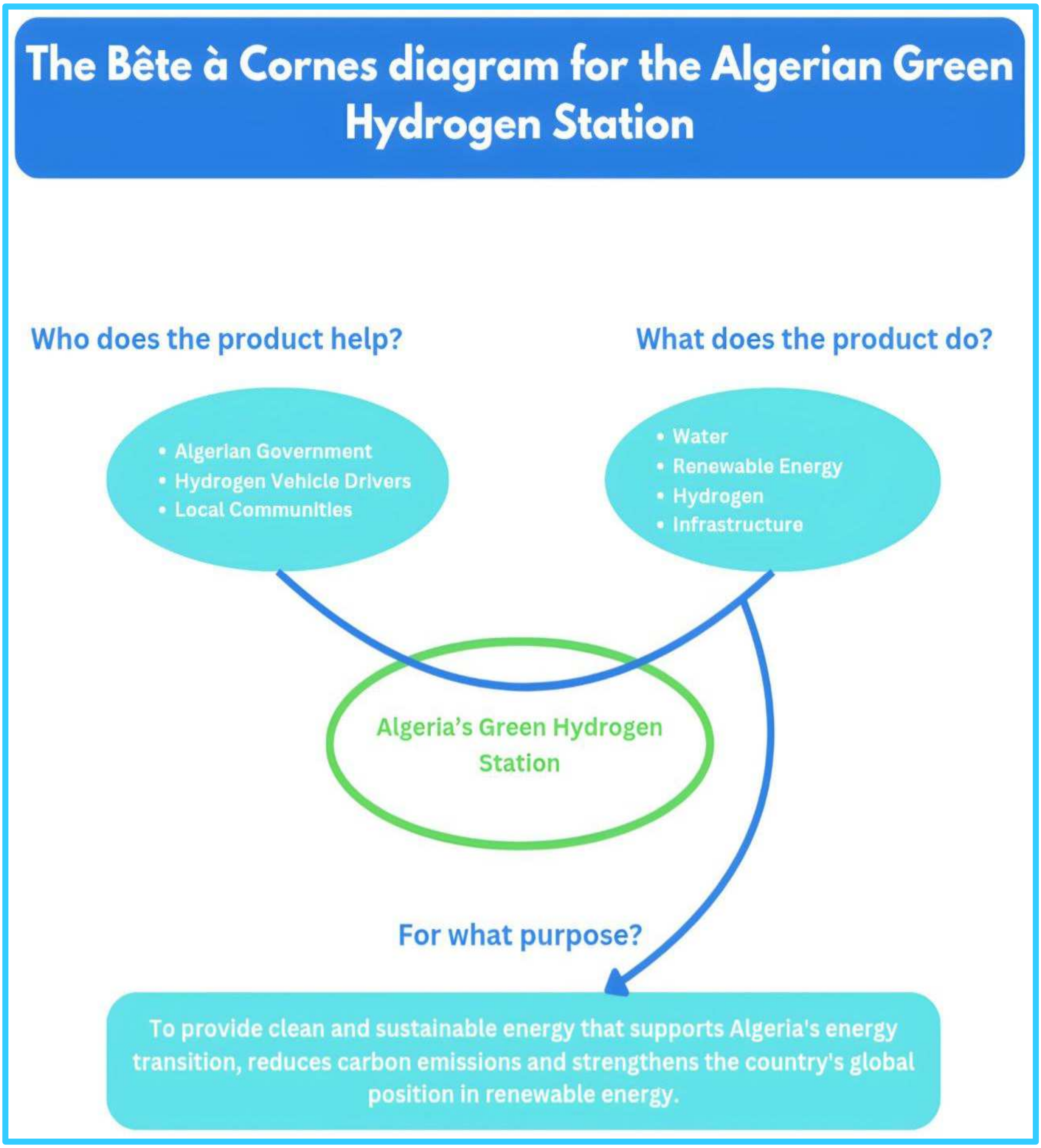


Figure (II-01): Bête à Cornes Diagram

- **Description of Bête à Cornes Diagram :**

The "Bête à Cornes" (or "Horned Beast") diagram is used to identify and define the main functions of a product or system by answering three fundamental questions : "Who does the product help ?", "What does the product do ?", and "For what purpose ?". This diagram aims to clarify the value and purpose of the product within its broader context.

Beneficiaries of the Station (Who does the product help ?) :

- **Algerian Government :** The station supports Algeria's national energy transition strategy, positioning the country as a leader in clean energy. It aligns with international climate agreements by reducing carbon emissions.
- **Drivers :** Offers hydrogen refuelling for vehicles (cars, buses, trucks) as a clean alternative to gasoline and diesel.
- **Local Communities :** Creates direct and indirect job opportunities, improves air quality by reducing pollution, and promotes sustainable development.

Functionality of the Station (What does the product do ?) :

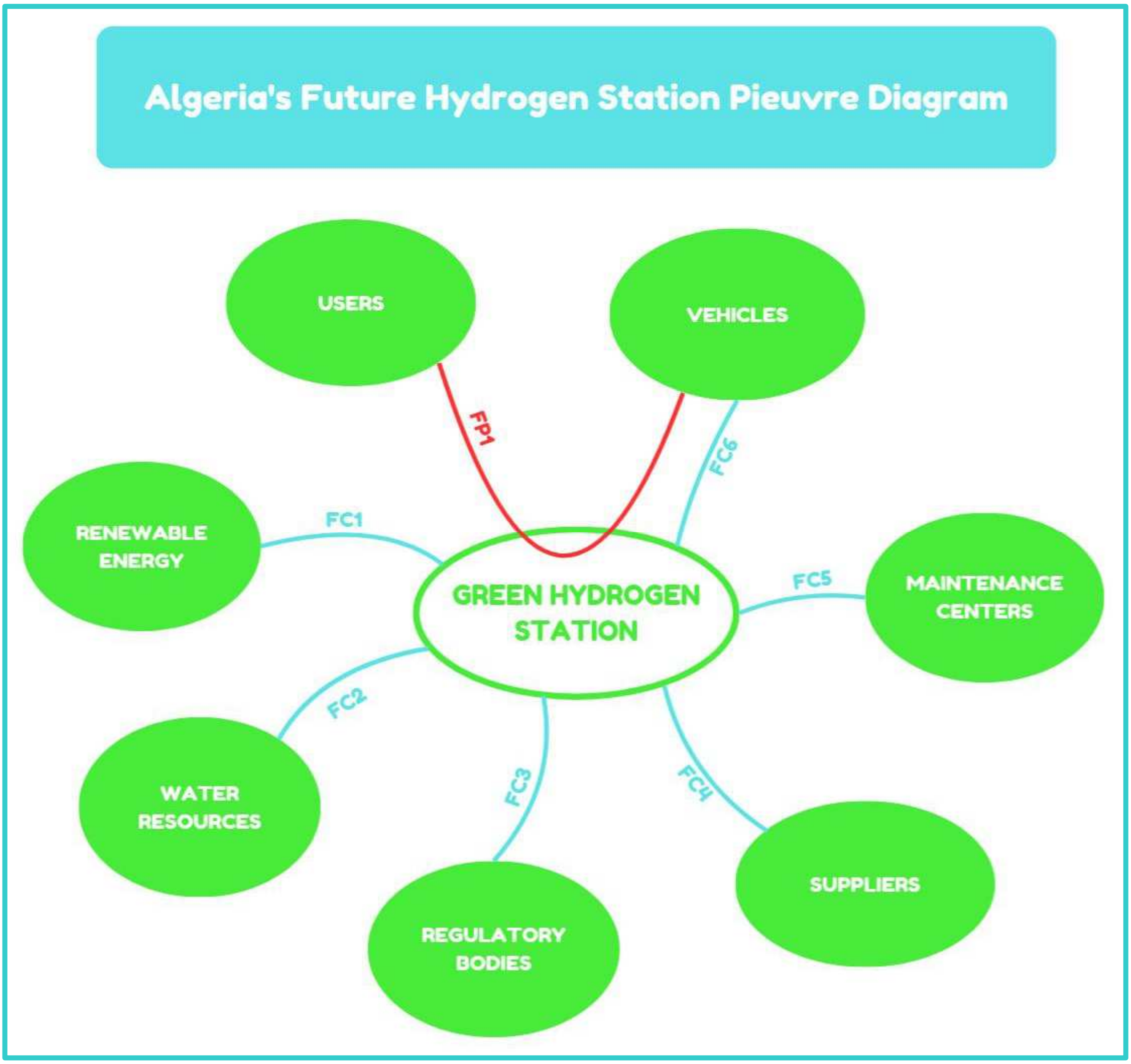
- **Water :** Water serves as a primary input for electrolysis, where it is split into hydrogen and oxygen.
- **Renewable Energy :** Solar energy (via photovoltaic panels) and wind energy (via turbines) generate electricity to power the station, ensuring sustainable production.
- **Hydrogen :** The station produces 99.97% pure green hydrogen through electrolysis, which is then compressed, cooled, stored in containers and distributed to vehicles.
- **Infrastructure :** Includes smart distribution networks, secure storage units, and modern refueling stations equipped with advanced technologies to ensure efficiency and safety.

Strategic Purpose (For what purpose ?) :

The station aims to achieve a fundamental objective :

- **Supporting energy transition and reducing carbon emissions :** Reducing carbon dioxide emissions by replacing fossil fuels with green hydrogen in the transport sector.

8.2. Pieuvre Diagram:



0**Figure (II-02):** Pieuvre Diagram

- **Table of Functions and Constraints (FP/FC):**

Function	Description
FP1	Meet the end-users needs for green hydrogen fuel
FC1	Utilize renewable energy (solar and wind) for hydrogen production
FC2	Use water resources (purified) as a raw material for hydrogen production
FC3	Comply with regulations and standards set by regulatory bodies
FC4	Obtain necessary materials, equipment, and services from suppliers
FC5	Utilize maintenance center services to ensure efficient station operation
FC6	Provide hydrogen fuel for vehicles that use it

Table (II-02): Functions and Constraints

- **Description of the Pieuvre Diagram:**

The Pieuvre diagram illustrates the relationships between the "Green Hydrogen Station" and various stakeholders and external elements with which it interacts. This diagram represents an analytical approach to identify the main and complementary functions of the system.

Central Function :

- **Green Hydrogen Station :** This is the core of the system, and the interactions surrounding it show the purpose of its existence and how it connects with its environment.

Interactions and Relationships : Interactions are represented by lines connecting the central function to external elements, with labels indicating the type of function :

- **FP1 (Main Function / Performance Function) :** Connects the **Green Hydrogen Station** to **Users**.

Description : This is the main performance function that describes the direct relationship between the station and the end-user of hydrogen fuel, ensuring their needs are met.

- **FC1 :** Connects the **Green Hydrogen Station** to **Renewable Energy**.

Description : This function represents the station's reliance on renewable energy sources (such as solar and wind power) for hydrogen production.

- **FC2 :** Connects the **Green Hydrogen Station** to **Water Resources**.

Description : This function indicates the station's need for water as a raw material for the electrolysis process to produce hydrogen.

- **FC3 :** Connects the **Green Hydrogen Station** to **Regulatory Bodies**.

Description : This function reflects the station's commitment to the legal and environmental regulations and standards set by the competent authorities.

- **FC4 :** Connects the **Green Hydrogen Station** to **Suppliers**.

Description : This function highlights the station's dependence on external suppliers for providing equipment, spare parts, and other services necessary for its operation and maintenance.

- **FC5 :** Connects the **Green Hydrogen Station** to **Maintenance Centers**.

Description : This function indicates the need for maintenance services to ensure the continuity and efficiency of the station's operations.

- **FC6 :** Connects the **Green Hydrogen Station** to **Vehicles**.

Description : This function represents the primary purpose of the station, which is to provide hydrogen fuel for vehicles that run on this fuel.

8.3. FAST Diagram:

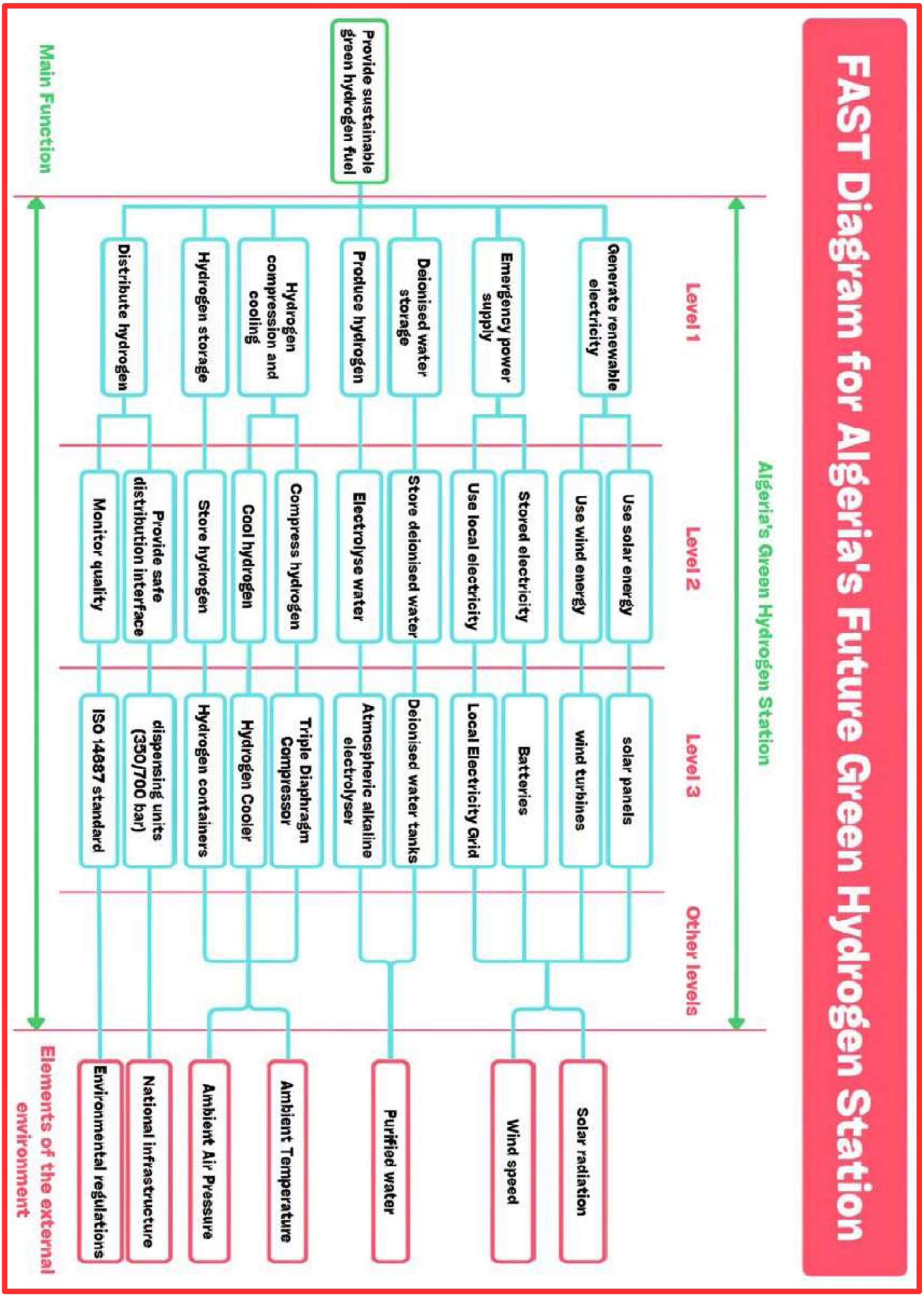


Figure (II-03): FAST Diagram

- **Description of FAST Diagram :**

FAST diagram visually breaks down the main function of "Provide sustainable green hydrogen fuel" into increasingly detailed levels, showing the relationships between different functions and the external elements that influence them.

The diagram is structured into several levels :

Main Function :

- **Provide sustainable green hydrogen fuel**

Level 1 (Core Functions) : These are the primary high-level functions required to achieve the main goal.

- Generate renewable electricity
- Emergency power supply
- Deionised water storage
- Produce hydrogen
- Hydrogen compression and cooling
- Hydrogen storage
- Distribute hydrogen

Level 2 (Sub-Functions - How Level 1 is Achieved) : This level details the methods or sub-functions used to accomplish the Level 1 functions.

- **For "Generate renewable electricity" :**
  - Use solar energy
  - Use wind energy
- **For "Emergency power supply" :**
  - Stored electricity
  - Use local electricity
- **For "Deionised water storage" :**
  - Store deionised water
- **For "Produce hydrogen" :**
  - Electrolyse water
- **For "Hydrogen compression and cooling" :**
  - Compress hydrogen
  - Cool hydrogen
- **For "Hydrogen storage" :**

    - Store hydrogen
  - **For "Distribute hydrogen" :**
    - Provide safe distribution interface
    - Monitor quality

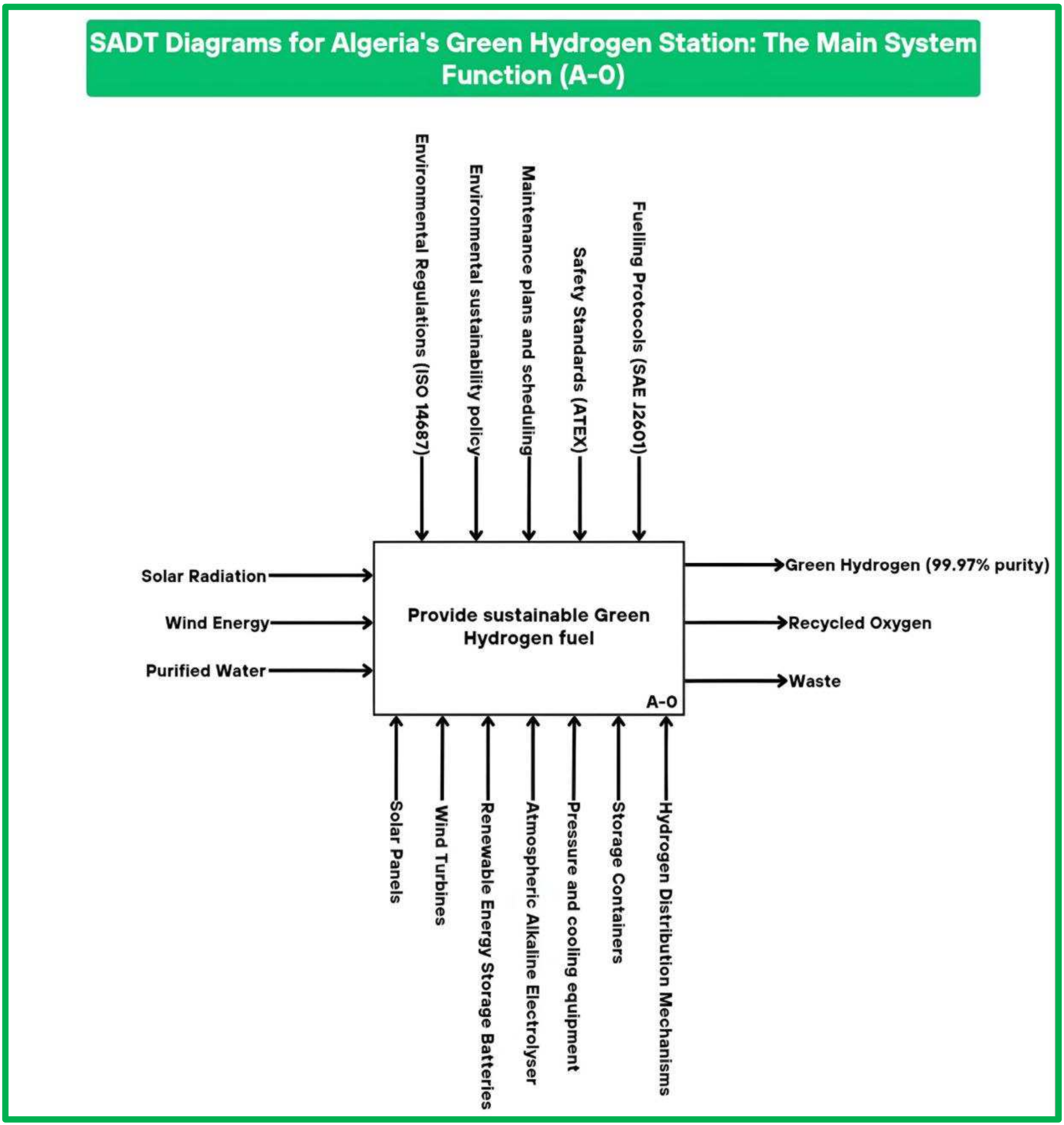
Level 3 (Mechanisms/Specifics - How Level 2 is Achieved/Implemented) : This level specifies the mechanisms, equipment, or specific actions taken for the Level 2 functions.

- **For "Use solar energy" :** Solar panels
- **For "Use wind energy" :** Wind turbines
- **For "Stored electricity" :** Batteries
- **For "Use local electricity" :** Local Electricity Grid
- **For "Store deionised water" :** Deionised water tanks
- **For "Electrolyse water" :** Atmospheric alkaline electrolyser
- **For "Compress hydrogen" :** Triple Diaphragm Compressor
- **For "Cool hydrogen" :** Hydrogen Cooler
- **For "Store hydrogen" :** Hydrogen containers
- **For "Provide safe distribution interface" :** Dispensing units (350/700 bar)
- **For "Monitor quality" :** ISO 14687 standard

Other Levels / External Elements : These are external factors or inputs that influence or are required by the functions.

- **Connected to "Solar panels" :** Solar radiation
- **Connected to "Wind turbines" :** Wind speed
- **Connected to "Atmospheric alkaline electrolyser" :** Purified water
- **Connected to "Hydrogen Cooler" :** Ambient Temperature, Ambient Air Pressure
- **Connected to "Dispensing units" :** National infrastructure
- **Connected to "Monitor quality" :** Environmental regulations

8.4. SADT Diagram A-0 Level:



0Figure (II-04): SADT Diagram (A-O Level – System Compliance)

- **Description of SADT (A-O Level) Diagram :**

A-0 diagram represents the highest level of abstraction in the SADT methodology, showing the overall main function of the system and its primary inputs, outputs, controls, and mechanisms.

Main System Function (A-0) :

- Provide sustainable Green Hydrogen fuel

Inputs : These are the resources or raw materials consumed or transformed by the system.

- Solar Radiation
- Wind Energy
- Purified Water

Outputs : These are the products, services, or results generated by the system.

- Green Hydrogen (99.97% purity)
- Recycled Oxygen
- Waste

Controls : These are the guidelines, regulations, standards, or policies that govern or constrain how the function operates.

- Environmental Regulations (ISO 14687)
- Environmental sustainability policy
- Maintenance plans and scheduling
- Safety Standards (ATEX)
- Fuelling Protocols (SAE J2601)

Mechanisms : These are the resources, tools, or physical entities that execute the function.

- Solar Panels
- Wind Turbines
- Renewable Energy Storage Batteries
- Atmospheric Alkaline Electrolyzer
- Pressure and cooling equipment
- Storage Containers
- Hydrogen Distribution Mechanisms

8.5. SADT Diagram A0 Level :

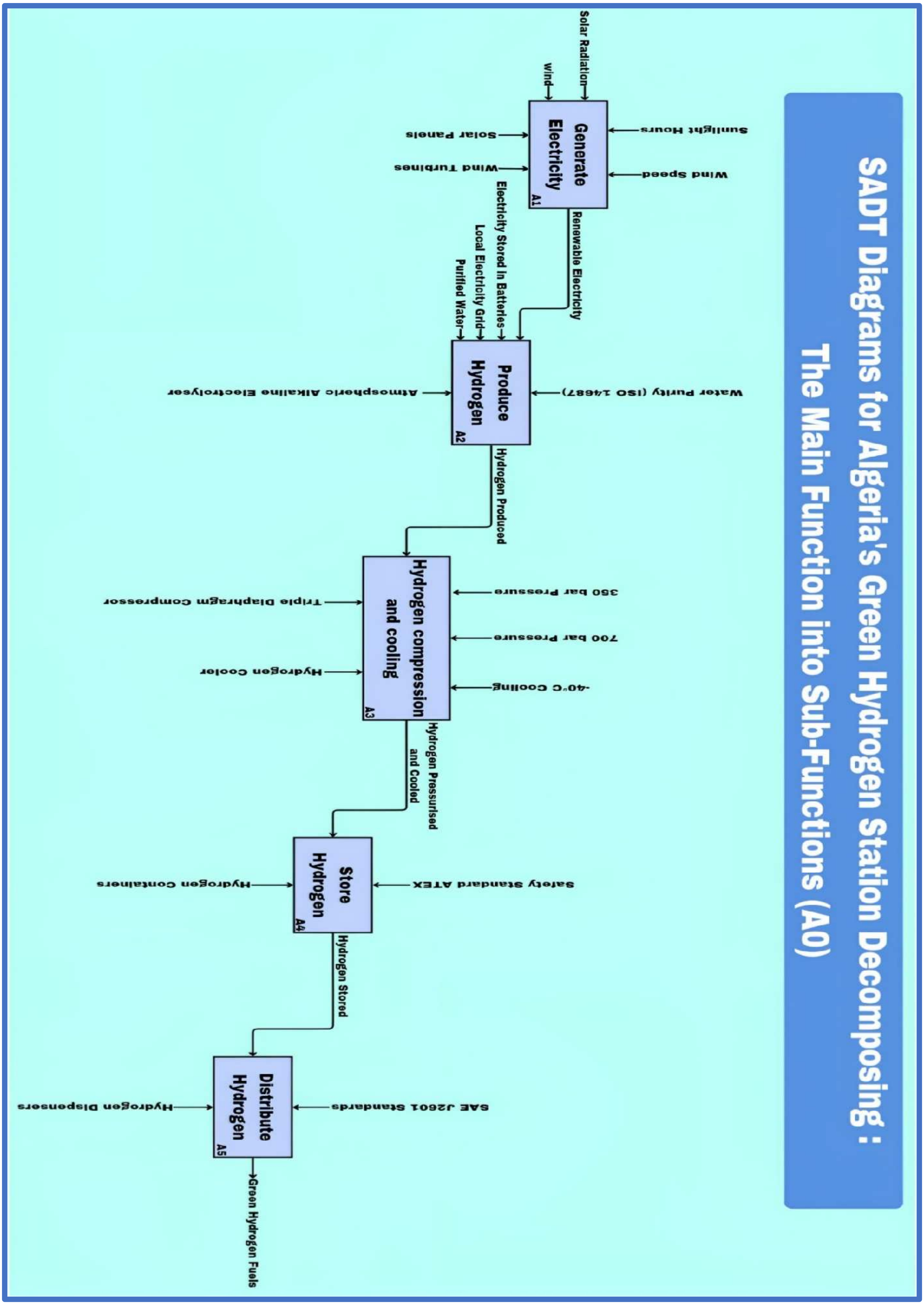


Figure (II-05): SADT Diagram (A0 Level – Functional Decomposition)

- **Description of SADT(A0 Level) Diagram:**

The SADT (Structured Analysis and Design Technique) diagram illustrates the main function of "Algeria's Green Hydrogen Station Decomposing" into sub-functions, starting with A0 : "The Main Function into Sub-Functions".

- **A1 : Generate Electricity :** This initial stage focuses on generating renewable electricity.

Inputs : Solar Radiation and Wind are the primary energy sources.

Controls/Mechanisms : Sunlight Hours, Wind Speed, Solar Panels, and Wind Turbines are the mechanisms used for generation.

Outputs : Renewable Electricity is produced. Electricity stored in batteries and Local Electricity Grid represent how the generated electricity is handled.

- **A2 : Produce Hydrogen :** This stage takes the generated electricity and uses it to produce hydrogen.

Inputs : Renewable Electricity and Purified Water are the main inputs.

Controls/Mechanisms : Water Purity and Atmospheric Alkaline Electrolyser are the mechanisms ensuring the quality and method of production.

Outputs : Hydrogen Produced.

- **A3 : Hydrogen Compression and Cooling :** The produced hydrogen is then prepared for storage.

Inputs : Hydrogen Produced.

Controls/Mechanisms : 350 bar and 700 bar Pressure, -40°C Cooling, Triple Diaphragm Compressor, and Hydrogen Cooler are the mechanisms and conditions for this process.

Outputs : Hydrogen Pressurized and Cooled.

- **A4 : Store Hydrogen :** This stage is dedicated to the storage of the processed hydrogen.

Inputs : Hydrogen Pressurized and Cooled.

Controls/Mechanisms : Safety Standard ATEX and Hydrogen Containers are critical for safe and effective storage.

Outputs : Hydrogen Stored.

- **A5 : Distribute Hydrogen :** The final stage involves the distribution of the stored green hydrogen.

Inputs : Hydrogen Stored.

Controls/Mechanisms : SAE J2601 Standards and Hydrogen Dispensers are the mechanisms and standards governing the distribution.

Outputs : Green Hydrogen Fuels.

9. Conclusion :

This chapter has systematically outlined the functional requirements for the establishment of Algeria's green hydrogen station, a critical milestone in the country's energy transition strategy. Through a comprehensive analysis, we have shown how Algeria's abundant renewable resources can be effectively utilised to produce, store and distribute green hydrogen according to international standards while meeting local operational needs.

Chapter 03:

Feasibility Study and Technical Aspects of a Future Green Hydrogen Station in Algeria

1. Introduction :

The third chapter of this study is central to achieving the objectives of this thesis. It aims to provide a detailed analysis of the study and design of an integrated hydrogen station, taking into account technical. The chapter begins with a feasibility study to assess the viability of the project, followed by an examination of the key components and technical specifications that make up the structural framework of the plant. The business model and market research are examined to ensure compatibility with local and global requirements, as well as integration with the Algerian environment in terms of resources and infrastructure. Environmental aspects are emphasised to enhance sustainability. The chapter also highlights compliance with international standards for quality assurance and safety. Finally, the chapter summarises the expected applications and operating principles, supported by examples of the technologies used. This comprehensive approach provides a solid foundation for the final station design.

2. Feasibility Study :

2.1. Demand Analysis:

Algeria has a great potential for renewable energy, especially solar and wind energy, which makes it an ideal place for the production of green hydrogen. This station aims to:

- Reduce greenhouse gas emissions.
- Diversify energy sources.
- Support the country's energy transition.

2.2. Objectives:

- Production of green hydrogen by electrolysis of water using renewable electricity.
- Distribution of hydrogen for light vehicles, buses and trucks.

2.3. Proposed Station Location:

Algeria has immense potential in the field of renewable energy, especially solar energy, making it an ideal location for the development of green hydrogen stations. Based on the available potential, the following locations are Proposed for future hydrogen stations [15] :

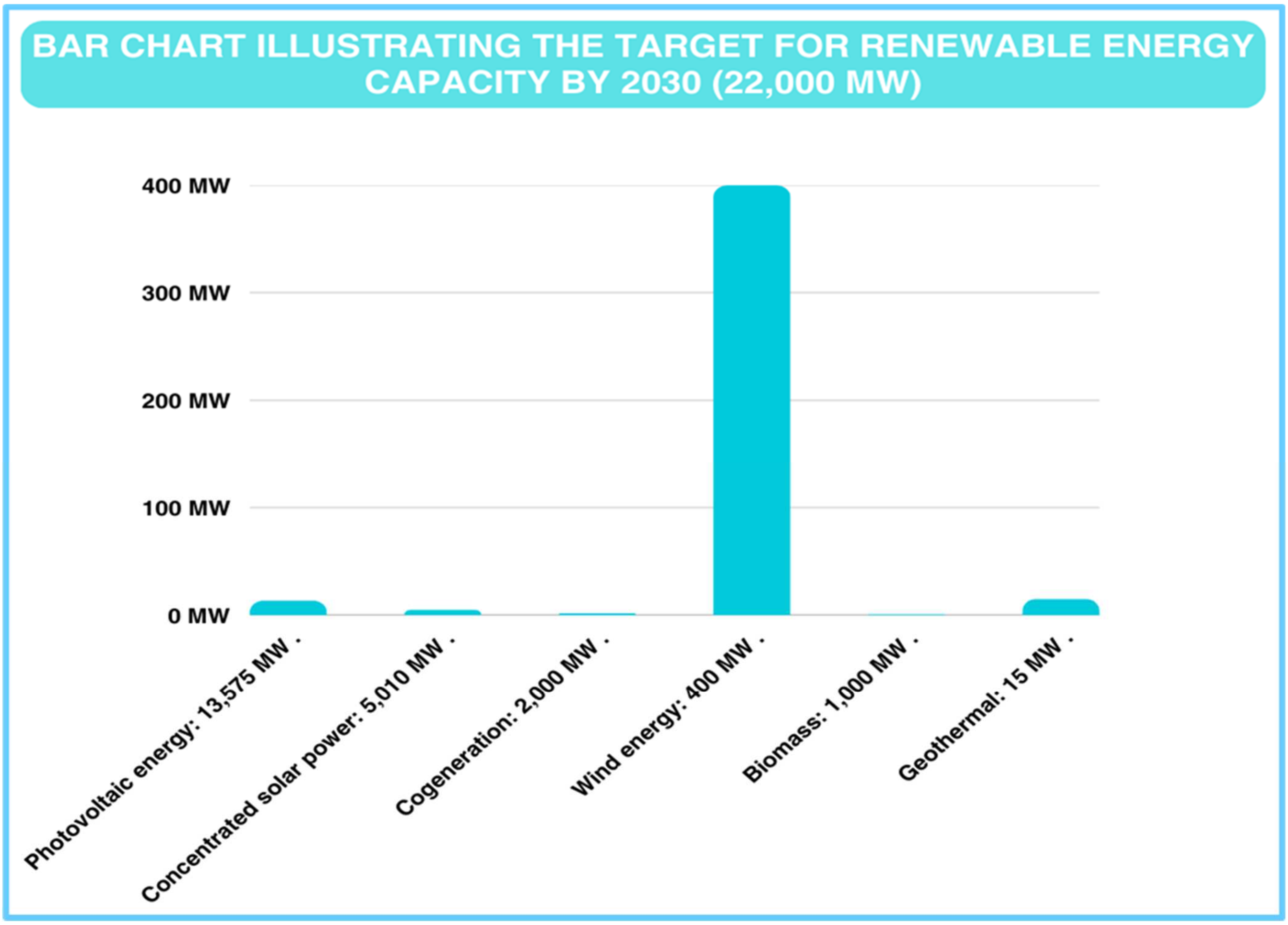


Figure (III-01): Bar chart illustrating the target for Renewable Energy capacity by 2030

a) High plateaus and the Sahara :

These areas have some of the highest solar radiation levels in the world, with up to 3,900 hours of sunshine per year. The solar energy available here exceeds 5.6 kWh/m² per year, making it ideal for hydrogen production by electrolysis using solar energy. [15]

b) Hassi R'mel (Laghouat) :

The region already has a hybrid (solar-gas) power plant with a capacity of 150 MW, providing an existing infrastructure that can be expanded to include hydrogen production. [15]

c) Adrar :

The region has a 10 MW wind farm and both wind and solar energy can be used together for hydrogen production. In addition, the North-Saharan Electricity Interconnection Project will facilitate the transmission of the energy produced. [15]

d) In Salah, Adrar, Timimoun and Béchar :

Large scale renewable energy plants will be installed in these regions as part of the national renewable energy programme, making them suitable for hydrogen production using solar thermal and photovoltaic energy. [15]

e) Oued Nechou (Ghardaia) :

The area has a 1.1 MW pilot photovoltaic plant, which can be developed to include hydrogen production. [15]

f) Northern regions :

Although solar radiation is lower than in the south, the northern regions can use wind energy and biomass for hydrogen production, especially in combined heat and power projects. [15]

g) Solutions for areas not suitable for producing hydrogen :

In regions with limited solar radiation or low wind resources (such as dense urban areas or remote mountainous areas), it is proposed to build hydrogen storage stations that act as distribution hubs to meet local demand. In such cases :

- Hydrogen produced in areas rich in renewable resources (e.g. the Sahara) is transported via pipelines or specialised carriers.
- At these stations, it is stored using safe technologies (such as pressurised or liquid-state storage) to ensure a steady supply to local industry or public transport.
- These stations are integrated with combined heat and power projects or smart grids to increase system efficiency.

This model ensures comprehensive coverage of hydrogen demand across Algeria, while reducing reliance on long-distance transport by establishing a national integrated network for production, storage and distribution.

3. Production and Storage Calculations :

Note: The calculations below are based on the technical specifications of the technologies used in the station and are detailed in the next section.

3.1. Fundamental Equations :

a) Daily Solar Energy Calculation :

$$E_{solar} = N_{panels} \times P_{panel} \times H_{sun}$$

Where :

N_{panels} : Number of solar panels

P_{panel} : Power output per panel (kW)

H_{sun} : Daily solar irradiance hours (8 hours)

b) Daily Wind Energy Calculation :

$$E_{wind} = N_{turbines} \times P_{turbine} \times CF \times 24$$

Where :

$N_{turbines}$: Number of wind turbines

$P_{turbine}$: Power output per turbine (kW)

CF : Capacity factor of the wind turbine

24 : Number of hours in a day

c) Law for Calculating Nember of Moles of a Gas at Standard Conditions :

At standard temperature and pressure (STP), which is commonly defined as :

Temperature = **0°C = 273.15 K**

Pressure = **1 atm**

$$n = V / V_m = V / 22.4$$

Where :

n: Number of moles (mol).

V: Volume of the gas in liters (L).

$V_m = 22.4$ L/mol: The molar volume of an ideal gas at STP.

d) Energy Required for the Electrolyzer :

$$E_{electrolyser} = Q_{H2} \times EC$$

Where :

$Q_{H2} = 485\ Nm^3/h \times 24 = 11640\ Nm^3/day$

$EC = 4.5\ kWh/Nm^3$

$$E_{electrolyser} = 11640 \times 4.5 = 52380\ kWh/day$$

3.2. Three Operational Cases :

a) Case 1 : Solar Energy Only

- **Number of Solar Panels Required :**

$$N_{panels} = 52380 \,/\, (0.55 \times 8) \approx 11905 \text{ panels}$$

b) Case 2 : Wind Energy Only

The annual average wind speed in Algeria is around 6.3 m/s at a height of 10 metres. Locations in southern Algeria are the windiest, with Adrar giving the highest annual average wind speed of 6.3 m/s, followed by Hassi el-Ramel at 6.1 m/s. [16]

Based on previous studies conducted in the Adrar region, the capacity factor of wind turbines ranges between 36% and 47%, depending on the type of equipment used and local operating conditions. For the purpose of this study, an average estimated value of 41.5% was adopted, in order to obtain a balanced and realistic result that avoids both excessive optimism and conservative underestimation. [17]

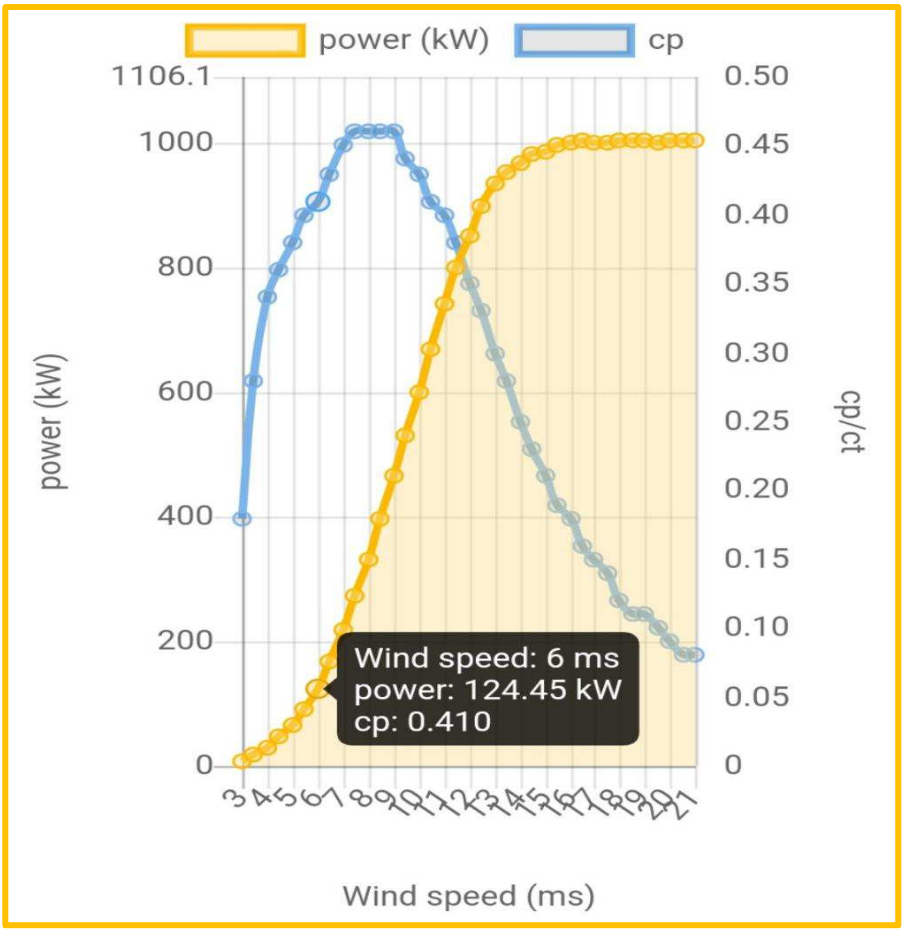


Figure (III-02): Wind Turbine power curve in terms of wind speed [18]

- **Number of Wind Turbines Required :**

$$N_{turbines} = 52380 \,/\, (124.45 \times 24 \times 0.415) \approx 43 \text{ turbines}$$

c) Case 3 : Hybrid Operation (Solar + Wind)

- **Objective :**

$$E_{solar} + E_{wind} = 52380 \text{ kWh/day}$$

- **Selection of Panels and Turbines :**
  - **Number of Solar Panels :**

4270 panels (JinKO550W$JinKO550W$)

  - **Solar Energy Generated :**

$$E_{solar} = 4270 \times 0.55 \times 8 = 18788 \text{ kWh/day}$$

  - **Remaining Energy from Wind :**

$$E_{wind} = 52380 - 18788 = 33592 \text{ kWh/day}$$

  - **Number of Wind Turbines Required :**

$$N_{turbines} = 33592 / (124.45 \times 24 \times 0.415) \approx 28 \text{ turbines}$$

3.3. Integration of Devices with the Local Grid :

a) Connecting the Electrolyser to the Public Electricity if required :

- Surplus renewable energy at peak times is stored in the NAS batteries for use when renewable energy sources are not available, and when all of the above energy sources are not available, the electrolyser is connected to the public grid to ensure that the plant continues to operate 24 hours a day.

b) Devices that are always connected to the Grid :

- Compressors, cooling systems, storage and dispensing units.
- **Purpose :** Reduce load on renewable energy sources and ensure operational stability.

3.4. Surplus Energy Storage in Batteries:

- **Maximum daily power requirement for full electrolyser operation:**

$$E_{total} = 52380 \text{ kWh/day (for Electrolyser)}$$

- **Number of NAS Ocean Freight Containers required:**

$$N_{batteries} = 52380 / 5800 \approx 9 \text{ Containers}$$

3.5. Water Requirement Calculation for Alkaline Electrolyser:

a) Standard data:

- **Electrolysis Reaction of Water:**

$2H_2O\ (l) \rightarrow 2H_2\ (g) + O_2\ (g)$

This implies :2 moles of water produce 2 moles of hydrogen gas.There fore, 1 mole of water produces 1 mole of H_2.

- Ideal Gas Law (at Standard Temperature and Pressure - STP):

1 mol of gas = 22.4 liters = 0.0224 m^3

- Molar Mass of Water :

$M(H_2O) = 18$ g/mol

- Density of Water (approximate):

  $\rho(H_2O) = 1000$ kg/m^3

b) Calculation steps :

- Calculate the number of moles of hydrogen produced daily:

$$n\ (H_2) = V\ (H_2) / Vm = 11640 / 0.0224 \approx 519643 \text{ mol}$$

- Determine the moles of water required:

$$n\ (H_2O) = n\ (H_2) = 519643 \text{ mol}$$

- Calculate the mass of water needed:

$$m\ (H_2O)= 519643 \text{ mol} \times 18 \text{ g/mol} = 9353571 \text{ g} = 9353.57 \text{ kg}$$

- Convert mass to volume:

$$V\ (H_2O) = 9353.57 \text{ kg} / 1000 \text{ kg/m}^3 = 9.35 \text{ m}^3$$

The Alkaline Electrolyzer requires approximately **9.35 m^3/day** of deionized water to produce **11640 Nm^3/day** of hydrogen.

3.6. Hydrogen Storage Calculations :

a) Daily production capacity of hydrogen by the electrolyser:

$$m_{electrolyser} = 1047 \text{ kg/day}$$

b) Rheinmetall's Multi-Element Gas Container Capacity :

Up to **at 380 bar**

- Storage capacity of a hydrogen container at a pressure of 350 bar is **1100 kg.**
- Calculate the storage capacity of a hydrogen container at a pressure of 700 bar:

$$350 \text{ bar} \rightarrow 1100 \text{ kg}$$

$$700 \text{ bar} \rightarrow m_{storag}$$

$$m_{storag} \text{ (at 700 bar)} = (1100 \times 700) / 350 = 2200 \text{ kg}$$

The storage capacity of the two hydrogen containers exceeds the daily production of hydrogen by the electrolyser because the hydrogen is divided into two parts prior to compression and cooling to meet the station's needs at two different pressures. This excess capacity can be used to store hydrogen produced in excess of demand during periods of low demand at the station. It can then be used later when demand is high, or transferred in liquid form to other stations that do not produce hydrogen by electrolysis, relying instead on ready hydrogen from other sources and providing distribution services only.

3.7. Operational Case Comparison Table :

Criterion	Solar Only Case	Wind Only Case	Hybrid Case
Number of Solar Panels	11905	0	4270
Number of Wind Turbines	0	43	28
Daily Energy (kWh)	52382	53299	53495
Grid dependency	High (night)	Medium	Low

Table (III-01): The three Operational Cases Comparison

4. Technology used :

4.1. JinKO Bifacial Solar Panels 535-555W Monocrystalline Module:

The JinKO Bifacial Solar Panels, offers a power range of 535W to 555W, utilizing Multi Busbar technology to enhance light absorption efficiency and reduce thermal loss. Designed to withstand harsh conditions such as humidity and ammonia, it supports wind loads up to 2400Pa and snow loads up to 5400Pa. Ideal for residential, commercial, and industrial projects, it features a 30-year warranty and achieves a 21.48% efficiency. The bifacial design enables 70%±5% rear-side energy generation, boosting overall power output. As a certified manufacturer with 14 years of experience, United Energy offers advanced technologies like PERC, HJT, and TOPCON, with no minimum order quantity (MOQ) required. [19]

Figure (III-03): JinKO Bifacial Solar Panels 535-555W Monocrystalline Module [19]

- **Technical Specifications Table:**

Parameter	Details
Power Range (W)	535 - 555 W
Maximum Efficiency	21.48%
Open Circuit Voltage (Voc)	49.54 - 50.30 V
Short Circuit Current (Isc)	13.83 - 14.07 A
Dimensions	2278 mm (D) × 1134 mm (W) × 35 mm (H)
Weight	28 kg
Number of Cells	144 cells (72×2)
Load Tolerance	Wind: 2400 Pa / Snow: 5400 Pa
Bifacial Efficiency	70% ±5%
Warranty	15-30 years
Certifications	TUV, CE, IEC, and others
Operating Temperature Range	-40°C to +85°C
Environmental Resistance	Salt mist, ammonia, high humidity

Table (III-02): JinKO Bifacial Solar Panels 535-555W Monocrystalline Module Specifications [19]

4.2. The AN Bonus 1000/54 Wind Turbine:

The AN Bonus 1000/54 is a 1 MW wind turbine manufactured by AN Wind Energie GmbH, a German company that ceased operations in 2005 and was acquired by Siemens Wind Power. The turbine starts operating at a wind speed of 3 m/s, reaches its rated power at 15 m/s, and shuts down at 25 m/s. Designed for onshore use, it can withstand extreme wind speeds of up to 60 m/s. [17]

The turbine features 3 fiberglass (GFK) blades with a 54.2-meter rotor diameter, produced by LM Glasfieber, and a planetary/spur gearbox (3-stage) from Flender. It uses an asynchronous generator (690 V, 50 Hz) by ABB and has been deployed in repowering projects like "Vollrather Höhe" in Germany. [18]

Figure (III-04): The AN Bonus 1000/54 Wind Turbine [18]

- **Technical Specifications Table:**

Parameter	Details
Rated Power	1000 kW
Cut-in Wind Speed	3 m/s
Cut-out Wind Speed	25 m/s
Survival Wind Speed	60 m/s
Rotor Diameter	54.2 m
Swept Area	2300 m²
Number of Blades	3
Blade Material	Fiberglass (GFK) - Manufactured by LM Glasfieber
Gearbox Type	Planetary/Spur (3-stage) - Manufactured by Flender
Generator	Asynchronous (690 V, 50 Hz) - Manufactured by ABB
Hub Height Options	50 / 60 / 70 m
Tower Type	Conical steel tube with anti-corrosion coating
Total Weight	155 tons

Application	Onshore
Original Manufacturer	AN Wind Energie GmbH (Germany)
Company Status	Defunct since 2005, now part of Siemens Wind Power

Table (III-03): AN Bonus 1000/54 wind turbine Specifications [18]

4.3. NAS Ocean Freight Containers:

NAS batteries are characterized by their high scalability, allowing capacity to be easily expanded to suit a single site or multiple separate locations. This makes them an ideal solution for delivering tens or even hundreds of megawatts over 6 to 7 hours of operation. Such a level of energy storage can defer or eliminate the need for investments in transmission, distribution, or generation infrastructure—especially when used alongside intermittent renewable energy sources to provide a clean and efficient solution. With a significantly shorter construction lead time compared to building or upgrading transmission lines and substations, NAS systems are a practical and efficient choice. The NAS system consists of battery enclosures, battery modules, and power conversion systems (PCS), with NGK responsible for the battery enclosures and modules while collaborating with several PCS manufacturers to complete the system. The design is based on a “Plug and Play” concept built into standard 20-foot shipping containers, which facilitates transport and installation while minimizing operational costs. The robust and insulated design also makes it suitable for installation in harsh weather conditions, as the enclosed battery modules can withstand a wide range of temperatures and environmental conditions. [20]

Figure (III-05): Conventional model of NAS Battery [20]

- **Technical Specifications Table:**

Category	Specification
Rated Output	DC5800kWh (BOL)
Configuration	Four container subunits, series connected. A subunit includes six NAS modules, each rated at DC41.7kW and DC245kWh.
Dimension	Conventional model of NAS Battery :6.1m (W) × 2.4m (D) × 2.6m (H) Nas Ocean Freight Containers :6.1m (W) × 5.6m (D) × 5.5m (H)
Weight	86 tonnes

Table (III-04): NAS Ocean Freight Containers [20]

4.4. Enduramaxx Drinking Water Tank:

The 30000 Litre potable drinking water tank is made of high quality, WRAS approved polyethylene (MDPE), ensuring the safe storage of drinking water. It is rotationally moulded for superior durability, impact resistance and weatherproofing, and is available in black, blue or natural colours. It is equipped with a Bye law 30 kit (Bye law 60 in Scotland) to prevent contamination and is suitable for agricultural, industrial and residential use, including for emergency water storage, food production and civil engineering projects. [21]

Figure (III-06): The 30000 Litre Potable Drinking Water Tank by Enduramaxx [21]

- **Technical Specifications Table:**

Parameter	Details
Capacity	30000 Litres (±3% tolerance)
Dimensions (mm)	Diameter: 3450 mm, Height: 3650 mm
Lid	620 mm
Outlet	2" plastic male outlet (other options available)
Material	WRAS-approved MDPE polyethylene, UV-stabilized & thermal-proofed
Certifications	WRAS, DWI (meets Regulation 31 for potable water)
Warranty	10 years
Key Applications	Drinking water storage, food industry, emergency supply, civil engineering projects
Optional Extras	-Type AB Airgap (for Fluid Category 5 compliance) - Thermal insulation - Custom fittings: level sensors, side access hatches, etc
Delivery	UK-wide direct shipping; Hiab (crane) delivery available on request
Customization	Multiple colors, PN16/ANSI flanges, side access hatches for maintenance

0Table (III-05): The 30000 Litre Potable Drinking Water Tank by Enduramaxx Specifications [21]

4.5. Nel A485 Atmospheric Alkaline Electrolyser:

The A485 Atmospheric Alkaline Electrolyser by Nel is one of the world’s most efficient systems for large-scale industrial hydrogen production. It features ultra-low energy consumption of 4.5 kWh/Nm³ and a maximum output of 485 Nm³/h (or 1,047 kg/day) of 99% pure hydrogen. Designed for scalability, multiple units can be combined (e.g., the A4000 system integrates 8 units to achieve 3,880 Nm³/h). Operating at low atmospheric pressure (0.03 bar), it ensures highest safety standards with minimal leakage risks. The system includes integrated hydrogen cooling, purification, and advanced automated controls. [22]

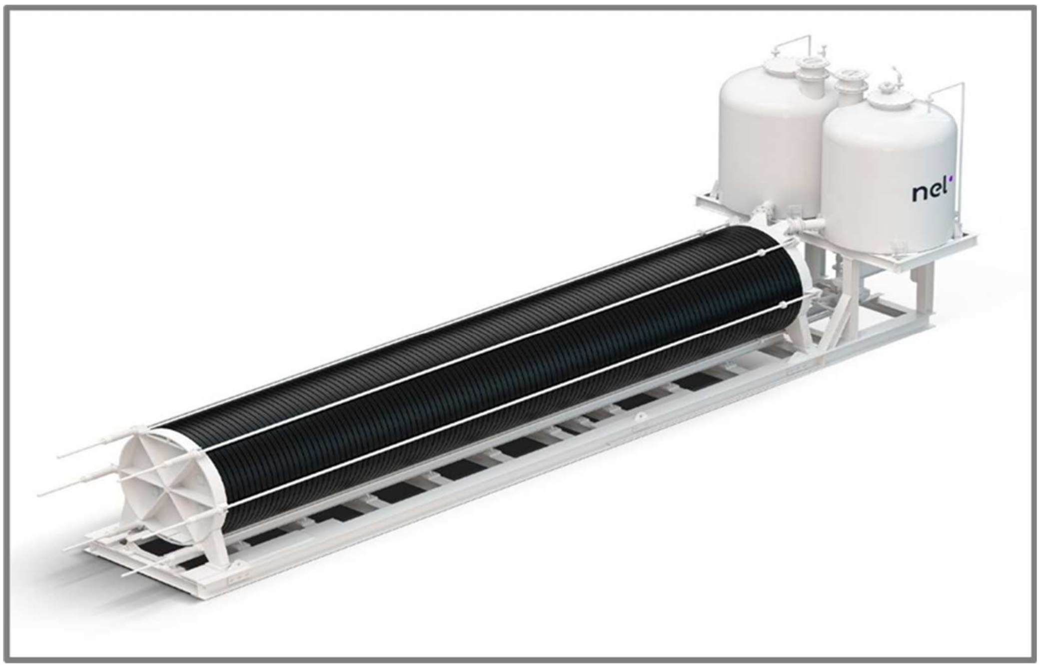


Figure (III-07): Nel Atmospheric Alkaline Electrolyser [22]

Figure (III-08): Nel Atmospheric Alkaline Electrolyser in real [23]

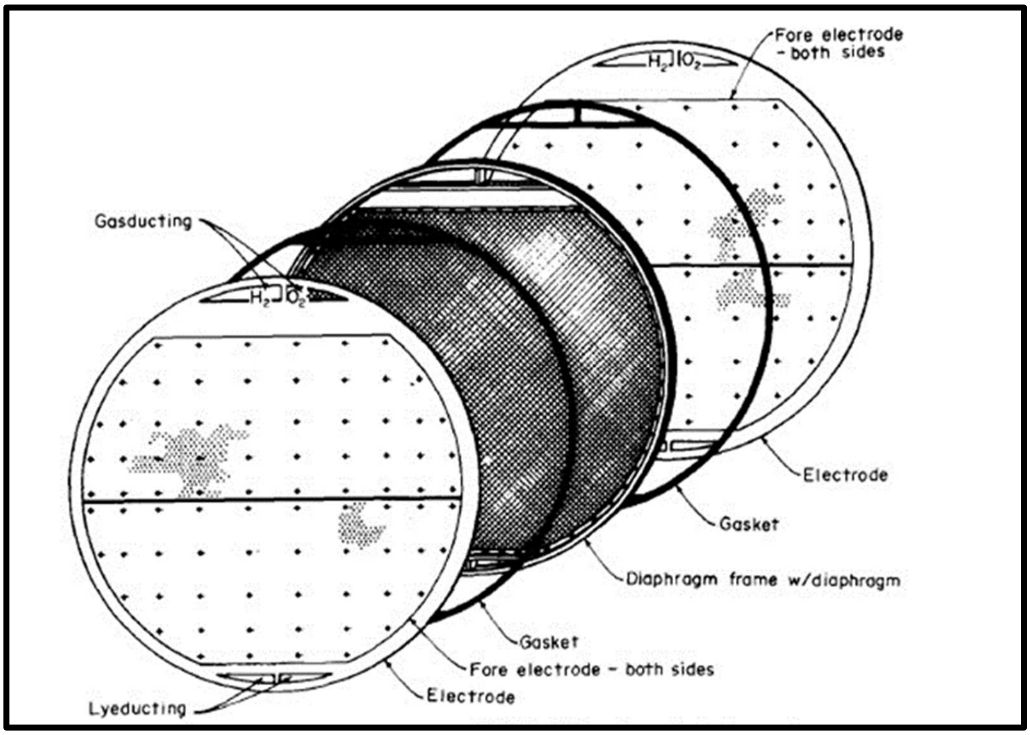


Figure (III-09):A clip of Nel Atmospheric Alkaline Electrolyser [23]

- **Technical Specifications Table:**

Parameter	Details
Maximum Hydrogen Production Rate	485 Nm³/h (±0/-3%)
Daily Production Capacity	1047 kg/day (±0/-3%)
Turndown Range	15% to 100%
Operational/Design Pressure	0.03 bar / 0.1 bar
Operational/Design Temperature	80°C / 90°C
Ambient Temperature Range	5°C to 45°C
Maximum Electrical Current	5,150 A
Power Consumption (at 100% capacity)	4.5 kWh/Nm³ (or 50 kWh/kg)
Hydrogen Purity	99% (water-saturated, <1% oxygen)
Oxygen Purity	99.5% (water-saturated, <0.5% hydrogen)
Footprint	≈ 60 m²
Electrolyte Type	25% KOH Aqueous Solution
Key Applications	Ammonia Production, Biofuel Manufacturing, Energy Storage, Mining, Chemical Processing

Table (III-06): Nel Atmospheric Alkaline Electrolyser Specifications [22]

4.6. Containerised Triple Diaphragm Solution hydrogen compressor:

The Containerised Triple Diaphragm Solution hydrogen compressor by GILBARCO VEEDER-ROOT is a turnkey, plug and play system designed for hydrogen refueling stations. It features triple diaphragm technology for efficient compression, supporting inlet pressures from 10 bar to outlet pressures up to 900 bar, with flow rates reaching 1.85 kg/min at 500 bar (≈2500 kg/day). The system ensures high safety through leak detection, emergency shutdowns, and compliance with NFPA 2 standards. Scalable and modular, it offers a service life exceeding 20 years, and is ideal for refueling cars (3-5 minutes), buses (<10 minutes), and trucks (<15 minutes).

[24]

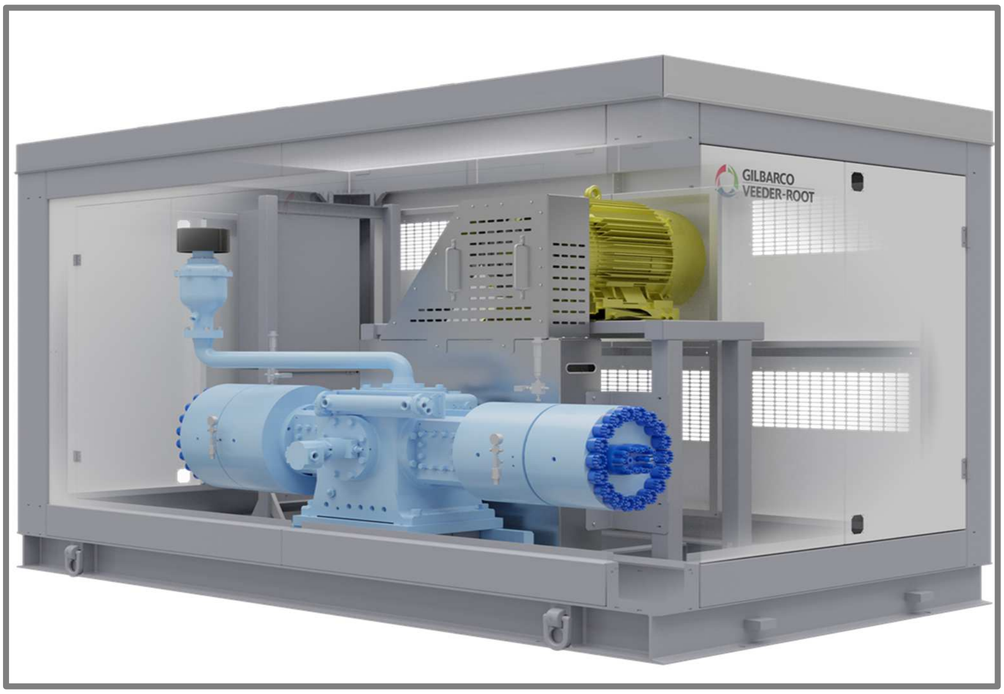


Figure (III-10): Containerised Triple Diaphragm Solution Hydrogen Compressor [24]

- **Technical Specifications Table:**

Parameter	Details
Minimum Inlet Pressure	10 bar
Maximum Outlet Pressure	900 bar
Flow Rate	-Up to 0.91 kg/min at 250 bar (≈ 1200 kg/day) -Up to 1.85 kg/min at 500 bar (≈ 2500 kg/day)
Compression Stages	Single or dual-stage (up to 4 stages per system)
Power Consumption	Up to 200 HP (160 kW)
Operating Temperature	Gas: 0 – 40°C / Ambient: -29 – 49°C
Integrated Components	Heat exchanger, pressure regulation, volume regulation
Maintenance Intervals	4000 – 2000 operating hours
Service Life	20 + years
Dimensions	417 cm (D) × 224 cm (W) × 234 cm (H)
Applications	Car refuelling (3-5 min), buses (<10 min), trucks (<15 min)

Standards Compliance	NFPA 2
Technical Support	Remote web-enabled diagnostics and aftersales services

Table (III-07): Containerised Triple Diaphragm Solution Hydrogen Compressor Specifications [24]

4.7. Hydrogen Cooler by Frigor Tec:

The HydrogenCooler units by FrigorTec GmbH (Germany) are specifically designed for the hydrogen industry, providing cooling solutions for electrolysis plants (e.g., AEL, PEM, HTE, AEM) and hydrogen refuelling stations. These units dissipate heat generated during production and compression processes, ensuring hydrogen purity of up to 99.9% by condensing residual moisture. They are built for continuous operation and can be customized for stationary or mobile (containerized) production. [24]

For refuelling stations, the system cools hydrogen to -40°C for cars (700 bar pressure) and 350 bar for trucks, featuring a flexible modular design that adapts to rapid load fluctuations. The units utilize the Siemens S7 control system for optimal process automation and remote diagnostics, supported by a global service network. [25]

Figure (III-11): Cooling technology for Refuelling Stations Hydrogen Cooler by Frigor Tec [25]

- **Technical Specifications Table:**

Parameter	Details
Application Areas	- Electrolysis plants (AEL, PEM, HTE, AEM) - Hydrogen refuelling stations
Required Temperature	Down to -40°C (for 700 bar pressure)
Cooling Pressures	350 bar (trucks) / 700 bar (cars)
Hydrogen Purity	Up to 99.9%
Control System	Siemens S7 (automation, remote diagnostics)
Design	Modular and customizable to site requirements
Cooling Modes	- Separate cooling for electrolysers and compressors (small systems) - Central cooling (large systems)
Certifications	Compliant with DIN EN ISO 9001:2015
Technical Support	Global service network

Table (III-08): Cooling Technology for Refuelling Stations Hydrogen Cooler by FrigorTec Specifications [25]

4.8. Rheinmetall’s Multiple-Element Gas Container (MEGC):

Rheinmetall’s Multiple-Element Gas Container (MEGC) is an advanced solution for hydrogen storage and transport, featuring Type IV pressure tanks capable of withstanding pressures up to 700 bar. The system offers comprehensive maintenance services and smart IoT integration, while fully complying with transportation regulations for road (ADR), rail (RID), and inland waterway (ADN) use. Key innovations include GEN II multi-filament winding technology, which reduces manufacturing time and carbon fiber consumption, and a storage capacity of up to 1100 kg of hydrogen at 380 bar. With IoT-enabled predictive maintenance and lifetime optimization, the MEGC is ideal for clean energy and mobility applications. [26]

Figure (III-12): Rheinmetall’s Multiple Element Gas Container [26]

- **Technical Specifications Table:**

Feature	Details
Pressure Range	350 – 700 bar
Vessel Type	Type IV
Available Lengths	20 FT / 40 FT (scalable)
Hydrogen Capacity	Up to 1100 kg (at 380 bar)
Regulatory Compliance	ADR (road), RID (rail), ADN (inland waterway)
Innovative Technologies	- GEN II multi-filament winding technology - GEN III IoT-enabled smart maintenance system
Key Benefits	- Reduced production time and carbon fiber use - Increased storage capacity - Predictive maintenance and lifetime maximization

Table (III-09): Rheinmetall’s Multiple Element Gas Container Specifications [26]

4.9. Gilbarco Veeder Root Hydrogen Dispenser:

The GILBARCO VEEDER-ROOT hydrogen dispenser is designed to refuel fuel cell electric vehicles at pressures of 350 bar or 700 bar with adaptable configurations including European or North American designs. The unit accommodates customisable arrangements such as single/dual sides, lane/island orientations and single/two hoses per side. It provides standard flow (3. 6 kg/min) or high flow (7. 2 kg/min for 350 bar only) using Coriolis mass flow measurement and superior cooling through diffusion bonded heat exchangers. [26]

The unit integrates effortlessly with payment terminals, automation systems and POS protocols, and features a 15″ multimedia display for user engagement. It complies with CE, ATEX, SAE J2601, ISO/NFPA2 and other international standards to ensure safety and reliability. [27]

Figure (III-13): Gilbarco Veeder Root Hydrogen Dispenser [27]

- **Technical Specifications Table:**

Parameter	Details
Filling Pressures	350 bar (H35) / 700 bar (H70)
Flow Capacity	Standard: 3.6 kg/min / High: 7.2 kg/min (H35 only)
Hose Configuration	1 or 2 hoses per side, single or three inlet lines
Measurement Technology	Coriolis mass flow meter
Cooling System	Diffusion-bonded internal heat exchanger (single/dual channel)
Flow Control	Emerson control valve
Fuelling Protocols	SAE J2601, SAE J2601-2
Vehicle Communication	Communicative or non-communicative (protocol-compliant)
Power Requirements	Europe: 220 VAC, 50 Hz / North America: 110 VAC, 60 Hz
Operating Temperature	-40°C to +50°C
Humidity Range	20-95% Rh (non-condensing)
Dimensions	(H) 2390 mm (H) × 1466 mm (W) × 610 mm ()
Certifications	CE, ATEX, PED, SAE, ISO/NFPA2, UL, and others
Branding Options	Custom logos on doors, hoses, and canopy

Table (III-10):GILBARCO VEEDER ROOT Hydrogen Dispenser Specifications [27]

Note: We have chosen these technologies to carry out the study and so that they are compatible with each other through their specifications provided by the manufacturing companies, but in case of the desire to materialise the project on the ground, many measures must be taken into account before implementing the project, and perhaps one of these influential measures is the cost of the project, so that technologies and equipment must be selected according to their productivity of the station and also their reasonable price.

5. Market research and business model :

5.1. Demand Analysis:

- **Target sectors:** Transport (light vehicles, buses, trucks).
- **Demand forecasts:** Short term (2025), medium term (2030) and long term (2040) demand estimates.

5.2. Economic model:

- **Investment costs:** Cost estimates for electrolyser, renewable energy, storage and distribution.
- **Selling price of hydrogen:** Current estimates suggest that the cost of producing green hydrogen using photovoltaic energy in Algeria ranges between $4 and $6 per kilogram, owing to its low solar electricity cost of $0.04/kWh. These figures place Algeria among the most competitive producers globally. [28]
- **Grants and incentives:** Identification of national and international support programmes.

6. Integration with the Algerian Environment :

- **Renewable Energy**: Utilizing Algeria's abundant solar and wind energy.
- **Future Expansion:** Modular design allowing for capacity increases as needed.
- **Technical Support:** Regular maintenance and global support from companies such as Frigor Tec, contracted when the plant's technology is purchased.

7. Environmental Considerations :

- **Zero Emissions :** The station produces no carbon emissions during operation.
- **Resource Efficiency :** Use of energy efficient cooling technologies (90% efficiency in compression systems).
- **Recycling :** Design of systems that are reusable or upgradeable.

8. Maintenance and Support :

- **Comprehensive Service Packages:** Including hydraulic system checks, compressors, and sensors.
- **Remote Support:** Access to the control system online for immediate diagnostics.
- **Training:** Providing training programs for Algerian personnel on station management.

9. Expected Applications :

- Supplying light vehicles (cars).
- Supplying heavy vehicles (trucks and buses).

10. Station Work Principle :

10.1. Renewable Electricity Generation (Based on Operational Cases):

a) Hybrid Case (Optimal Case):

- **Solar Energy:**

4270 JinKO Bifacial 550W solar panels generate **18788 kWh daily**.

- **Wind Energy:**

28 AN Bonus 1000/54 wind turbines (1 MW each) generate **34707 kWh daily**

- **Total Daily Production:**

53495 kWh, with surplus energy stored in **9** NAS containers to ensure uninterrupted operation during low renewable output.

b) Solar Only Case:

11905 solar panels generate **52382 kWh /day**. Surplus production is stored in batteries and, in the event of a shortfall in production (such as at night), the system is connected to the local electricity grid.

c) Wind Only Case:

43 wind turbines generate **53299 kWh/day**, with surplus production stored in batteries and the local grid used during times of renewable energy shortage.

10.2. Deionized Water Preparation:

The alkaline electrolyser requires approximately **9.35 m3/day** of deionised water to produce **11640 m^3/day** of hydrogen. Therefore, the station is equipped 3 deionised water tanks, each with a storage capacity of 30 m^3, which is sufficient to produce hydrogen for 9 days and then be refilled again.

10.3. Electrolysis Process:

- **Electrolyser Used:** Nel A485 Atmospheric Alkaline Electrolyser.
- **Daily Output:** 11640 Nm^3/ day of hydrogen with 99% purity.
- **Oxygen Byproduct:** Safely released into the atmosphere after purification to 99.5% purity.

10.4. Hydrogen Compression:

The produced hydrogen is split into two compressors that compress it to pressures of 700 bar and 350 bar to maximise storage space in the hydrogen containers.

10.5. Hydrogen Cooling:

The two Frigor Tec cooling units lower the temperature of the pressurised hydrogen to -40°C. This increases its density and reduces the risk of thermal expansion.

10.6. Hydrogen Storage:

Utilising two Rheinmetall MEGC containers designed for high pressure resistance.

- **Containers capacity:**
    - **At 350 bar pressure:** 1100 kg
    - **At 700 bar pressure:**2200 kg
- **Utilization of Additional Storage Capacity:** The extra storage capacity in the containers (at either 350 or 700 bar) provides operational flexibility, allowing for:
    - Storing excess hydrogen produced during periods of low demand.
    - Securing supply during high-demand periods or system downtimes.
    - Transferring surplus hydrogen to other stations that do not produce hydrogen via electrolysis but rely on external supply and provide only distribution services.
- **Designed:** Equipped with IoT-enabled monitoring for safety and efficiency.

10.7. Hydrogen Distribution:

- **Distributors:** Two Gilbarco Veeder Root dispensers support refuelling at 700 bar (3.6 kg/min for cars) and 350 bar (7.2 kg/min for trucks).
- **Safety and accuracy:** SAE J2601 compliant to prevent leaks and ensure accurate refuelling.

10.8. Integration with Local Infrastructure:

- **Operational Flexibility:** Prioritizes renewable energy, with grid or battery backup during shortages.
- **Monitoring Systems:** Include pressure temperature sensors, leak detectors, and emergency shutdown mechanisms.

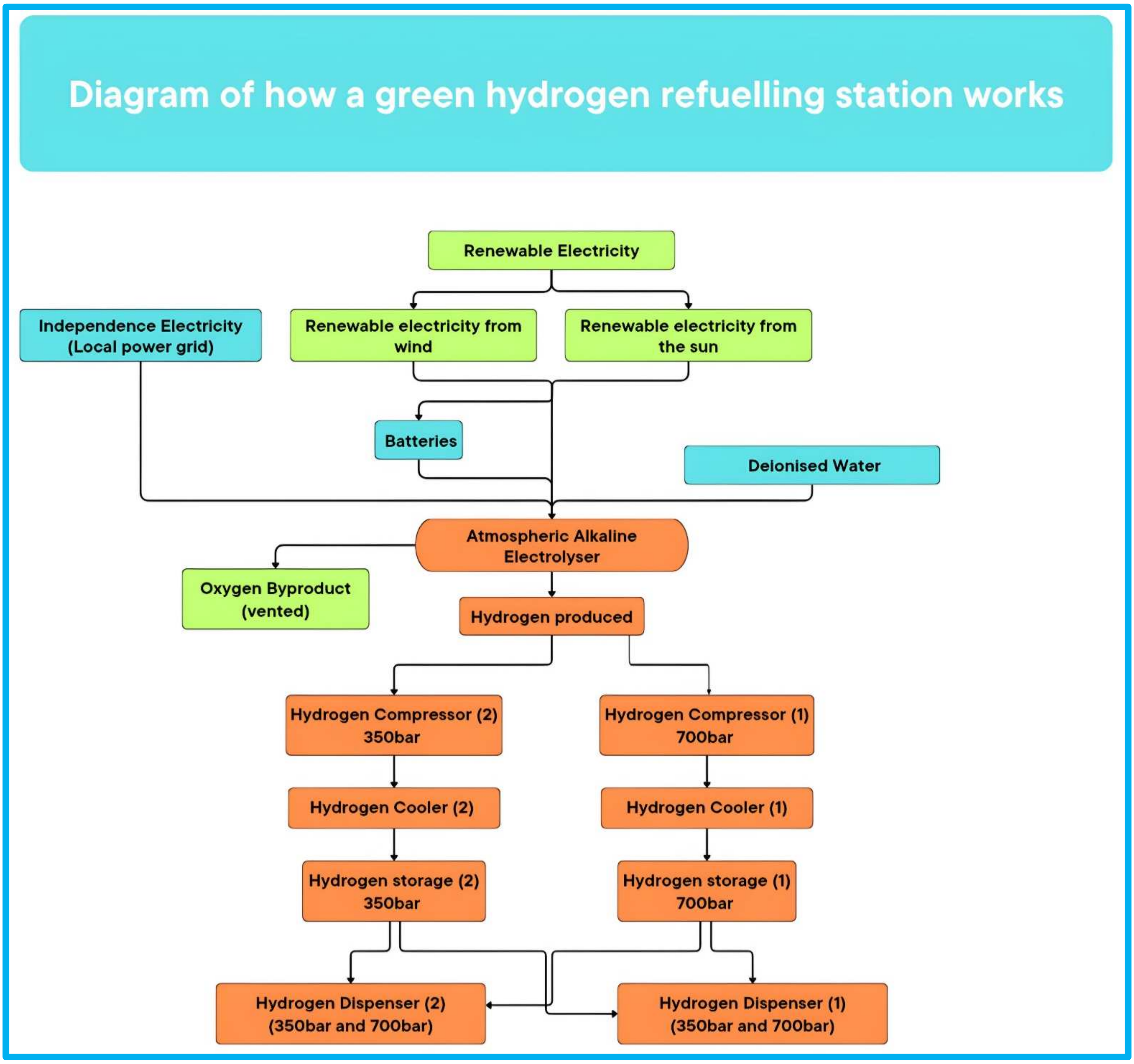
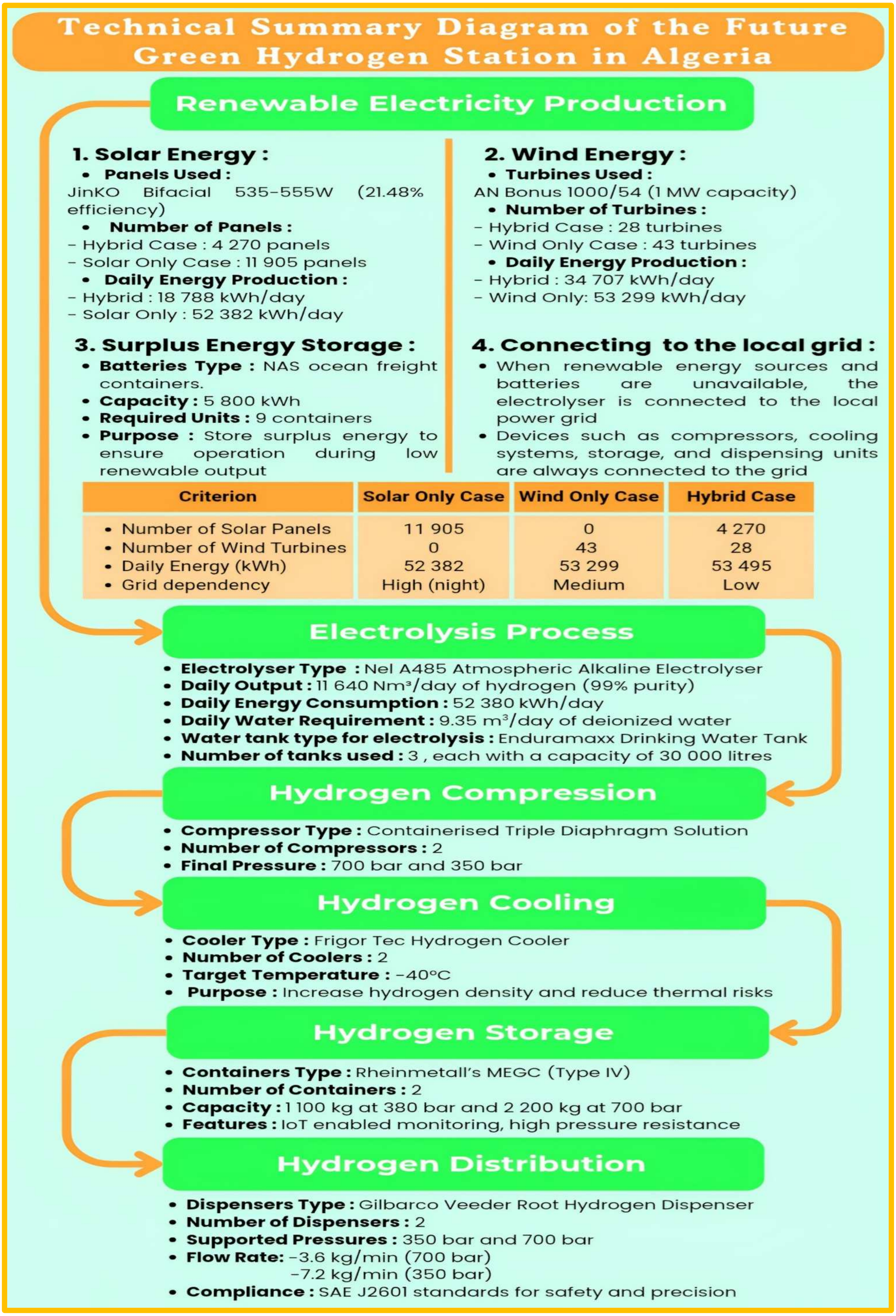


Figure (III-14): Diagram showing how a green hydrogen refuelling station works



Technical Summary Diagram of the Future Green Hydrogen Station in Algeria

Renewable Electricity Production

1. Solar Energy :

- **Panels Used :**

JinKO Bifacial 535-555W (21.48% efficiency)

- **Number of Panels :**

- Hybrid Case : 4 270 panels
- Solar Only Case : 11 905 panels

- **Daily Energy Production :**

- Hybrid : 18 788 kWh/day
- Solar Only : 52 382 kWh/day

2. Wind Energy :

- **Turbines Used :**

AN Bonus 1000/54 (1 MW capacity)

- **Number of Turbines :**

- Hybrid Case : 28 turbines
- Wind Only Case : 43 turbines

- **Daily Energy Production :**

- Hybrid : 34 707 kWh/day
- Wind Only: 53 299 kWh/day

3. Surplus Energy Storage :

- **Batteries Type :** NAS ocean freight containers.
- **Capacity :** 5 800 kWh
- **Required Units :** 9 containers
- **Purpose :** Store surplus energy to ensure operation during low renewable output

4. Connecting to the local grid :

- When renewable energy sources and batteries are unavailable, the electrolyser is connected to the local power grid
- Devices such as compressors, cooling systems, storage, and dispensing units are always connected to the grid

Criterion	Solar Only Case	Wind Only Case	Hybrid Case
• Number of Solar Panels	11 905	0	4 270
• Number of Wind Turbines	0	43	28
• Daily Energy (kWh)	52 382	53 299	53 495
• Grid dependency	High (night)	Medium	Low

Electrolysis Process

- **Electrolyser Type :** Nel A485 Atmospheric Alkaline Electrolyser
- **Daily Output :** 11 640 Nm³/day of hydrogen (99% purity)
- **Daily Energy Consumption :** 52 380 kWh/day
- **Daily Water Requirement :** 9.35 m³/day of deionized water
- **Water tank type for electrolysis :** Enduramaxx Drinking Water Tank
- **Number of tanks used :** 3 , each with a capacity of 30 000 litres

Hydrogen Compression

- **Compressor Type :** Containerised Triple Diaphragm Solution
- **Number of Compressors :** 2
- **Final Pressure :** 700 bar and 350 bar

Hydrogen Cooling

- **Cooler Type :** Frigor Tec Hydrogen Cooler
- **Number of Coolers :** 2
- **Target Temperature :** -40°C
- **Purpose :** Increase hydrogen density and reduce thermal risks

Hydrogen Storage

- **Containers Type :** Rheinmetall's MEGC (Type IV)
- **Number of Containers :** 2
- **Capacity :** 1 100 kg at 380 bar and 2 200 kg at 700 bar
- **Features :** IoT enabled monitoring, high pressure resistance

Hydrogen Distribution

- **Dispensers Type :** Gilbarco Veeder Root Hydrogen Dispenser
- **Number of Dispensers :** 2
- **Supported Pressures :** 350 bar and 700 bar
- **Flow Rate:** -3.6 kg/min (700 bar)
  -7.2 kg/min (350 bar)
- **Compliance :** SAE J2601 standards for safety and precision

Figure (III-15): Technical Summary Diagram of the Future Green Hydrogen Station in Algeria

11.Conclusion :

The chapter concludes with a comprehensive framework for the study and design of a viable hydrogen station in the Algerian context. The study confirmed the technical feasibility of the project. Key technical components and engineering specifications were identified to ensure operational efficiency, tailored to suit local conditions such as the availability of resources and infrastructure in Algeria. The study showed the project's compliance with global environmental standards through emission reduction and sustainable technologies. By reviewing examples of applied technologies and their operating principles, the chapter emphasized the adaptability of these solutions across diverse applications, from transportation to energy storage. As such, this chapter serves as a cornerstone for subsequent chapters, which will delve into the detailed design and practical implementation of the station, reinforcing Algeria's potential as a key player in the green hydrogen economy.

Chapter 04:

Design of the Future Green Hydrogen Station in Algeria

1. Introduction :

This chapter provides a detailed overview of the proposed system design for green hydrogen production. It will review the main components of the system from a purely design perspective, starting from renewable energy sources such as solar panels and wind turbines, moving through the electrolyser unit for hydrogen production, and concluding with hydrogen storage and compression systems. This section aims to provide a comprehensive visual and structural description of the system, clarifying how these components integrate and analysing their design functions to achieve the project's specified objectives. Design illustrative images for each part of the system will be included to enhance visual understanding of the proposed system's architectural and functional configuration.

2. The Program Used to Design the Station:

SolidWorks is an excellent program for designing green hydrogen stations thanks to its ability to provide accurate and comprehensive 3D designs. The program allows you to design all station components, from electrolysis devices and tanks to pumps and complex piping networks, in realistic detail.

Using SolidWorks, you can assemble these individual components together to create a complete 3D model of the station, helping you visualise the final shape and accurately determine dimensions and locations. This capability allows you to detect any potential interferences or issues between parts at a very early stage of design, before construction begins. These integrated design capabilities help simplify the complex design process.

3. Main Components and their Design :

3.1. Solar Panel Design :

The Jinko solar panel has the following dimensions:

2278 mm × 1134 mm × 35 mm, and the 24-panel array occupies an area of 10 metres. The design has only about 648 panels, which is not the number that the station actually needs. This number was chosen as a design sample only, as the actual number required is quite large.

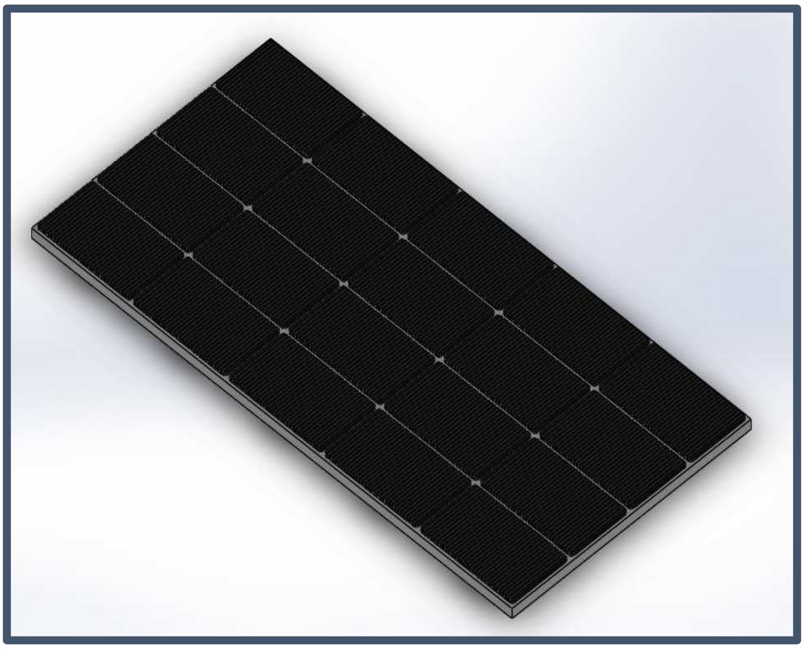


Figure (IV-01): Design of JinKO Bifacial Solar Panels 535-555W Monocrystalline Module

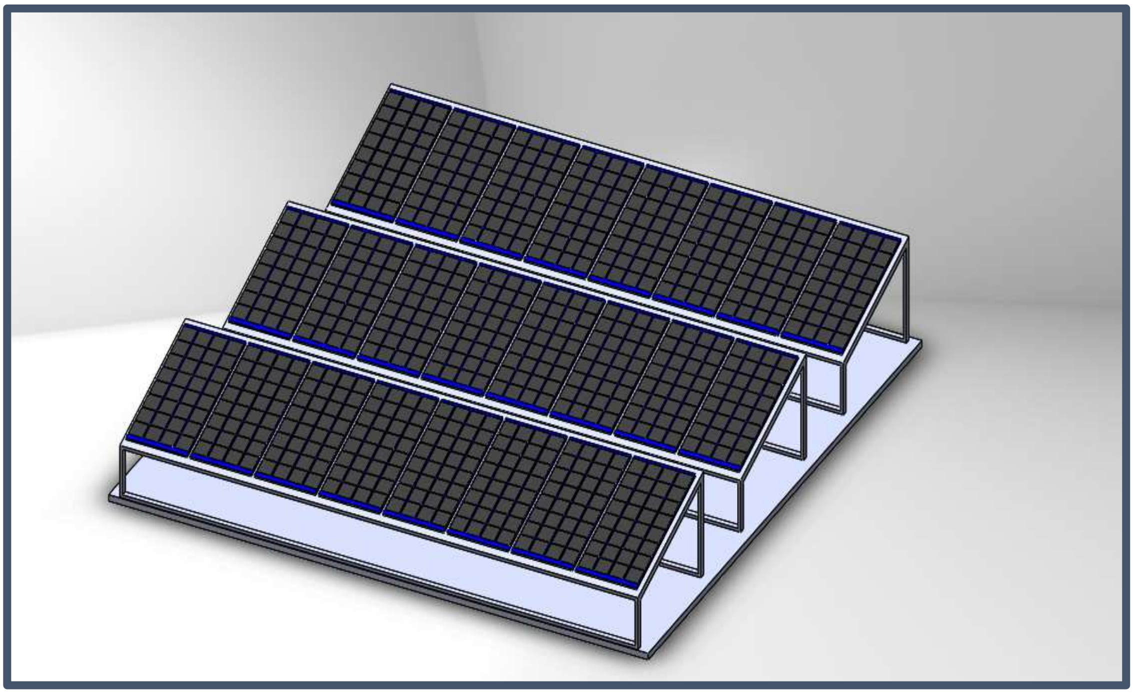


Figure (IV-02): Design for the installation of a set of 24 solar panels

3.2. Wind Turbine Design:

The wind turbine design is characterised by its sheer size.The base is about 12 metres in diameter and up to 60 metres high, while the rotor is about 54.2 metres in diameter.Eight wind turbines were used as a sample for the design, but this is not the actual number required by the station, as a large area is needed, which is difficult to represent in the design.

Figure (IV-03): Design of the AN Bonus 1000/54 wind turbine

3.3. NAS Container Storage Energy Design:

In the case of renewable energy storage batteries, they are specially designed, taking into account the dimensions of Nas shipping containers, which include four traditional Nas battery containers with dimensions of 6.1 (W) × 2.4 (D) × 2.6 (H) in a single storage container with dimensions of 6.1 (W) × 5.6 (D) × 5.5 (H) and the same traditional design to provide better representation in the design and reduce the space occupied. Nine containers were used to store the renewable electricity needed for the station.

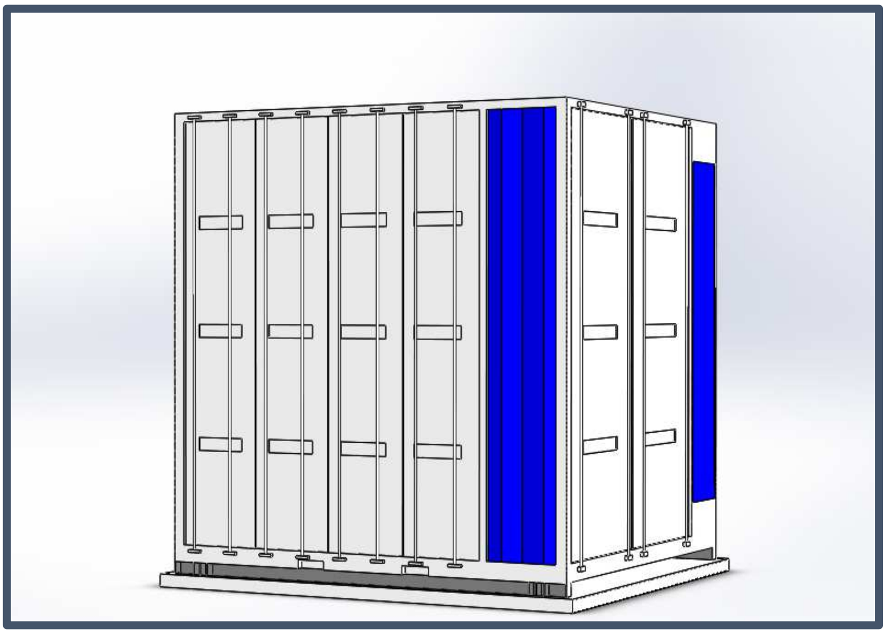


Figure (IV-04): NAS Container Storage Energy Design

3.4. Design of Enduramaxx Water Tank:

The deionised water tank has a diameter of approximately 3450 mm and a height of 3650 mm, occupying an area of 16000 m^2. Three tanks were used, which meets the needs of the station.

Figure (IV-05): Enduramaxx Water Tank

3.5. Nel Atmospheric Alkaline Electrolyser Design:

The electrolyser covers an area of about 60 m^2, Only one Nel atmospheric alkaline electrolyser was used to meet the needs of the water electrolysis process.

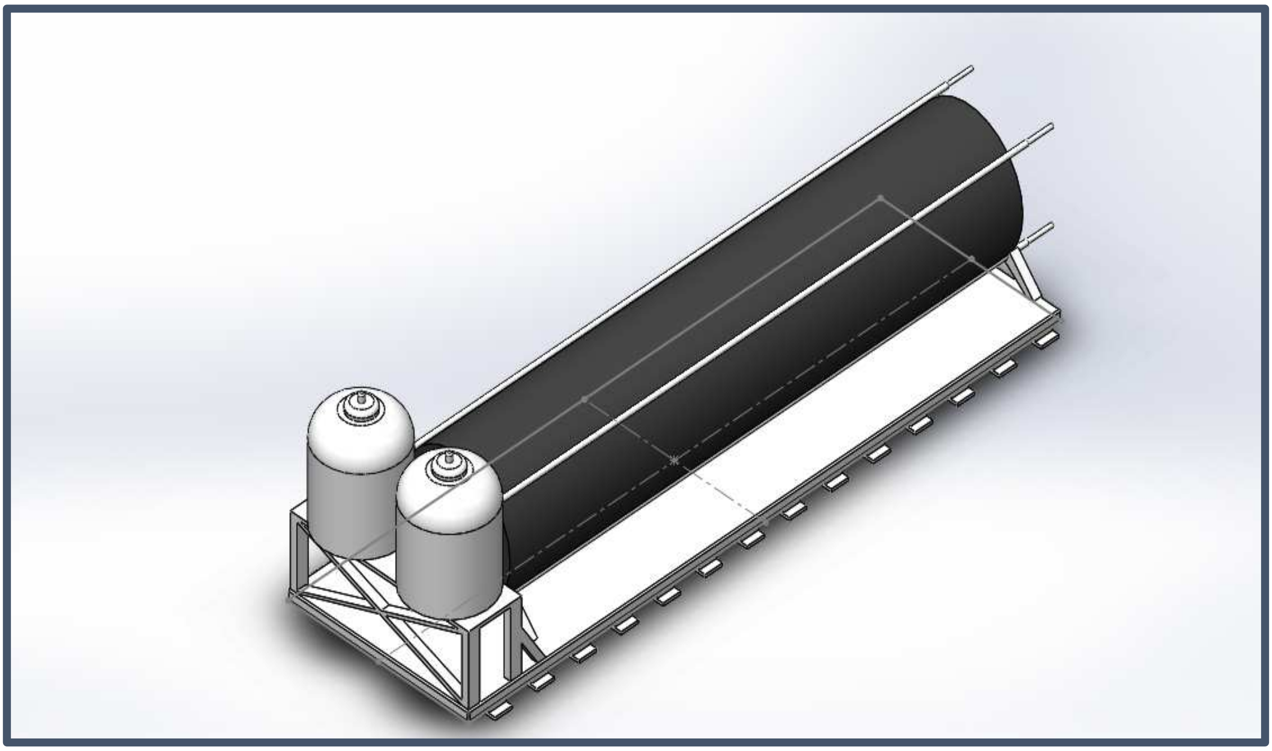


Figure (IV-06): Nel Atmospheric Alkaline Electrolyser Design

3.6. Triple Diaphragm Hydrogen Compressor Design:

The compressor covers an area of approximately 6318mm² and is 2340mm high. Two compressors were used in the station to cater for pressures of 350 bar and 700 bar.

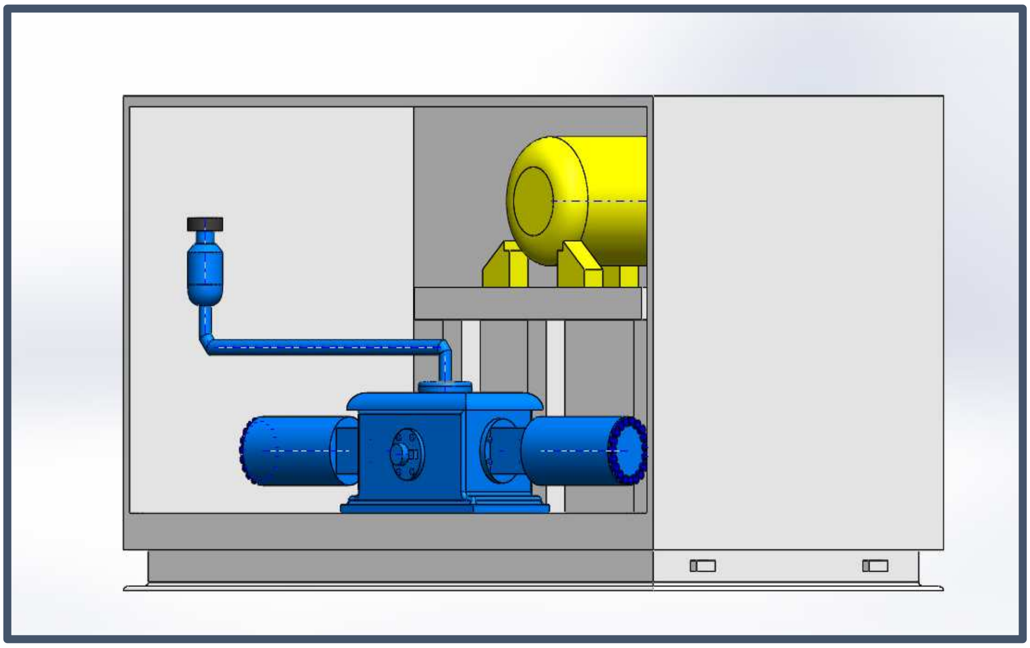


Figure (IV-07): Triple Diaphragm Hydrogen Compressor Design

3.7. Frigor Tech Hydrogen Cooler Design:

The cooler covers an area of four m^2 reaches a height of around four metres. Two cooler units were used in the system to meet the station's needs.

Figure (IV-08): Frigor Tech Hydrogen Cooler Design

3.8. Design of the Rheinmetall Multiple Element Gas Container:

The hydrogen containers cover an area of about 17878 mm^2. Two containers were used to meet the users' hydrogen needs.

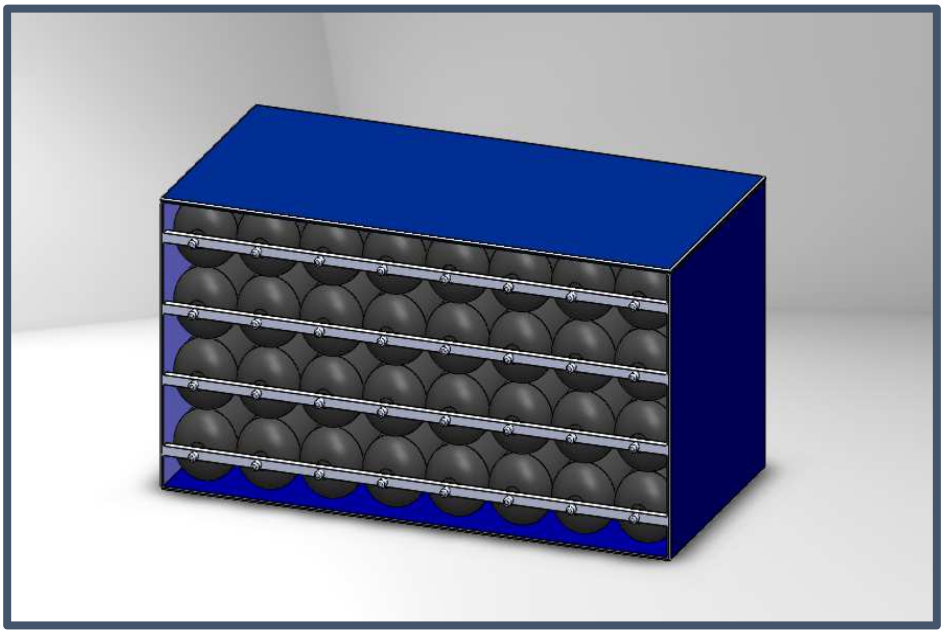


Figure (IV-09): Design of the Rheinmetall Multiple Element Gas Container

3.9. Design of the Gilbarco Veeder Root hydrogen dispenser:

The dispenser covers an area of 790 mm^2 and has the following dimensions 2390 mm (H) × 1466 mm (D) ×610 mm (W). Two dispensers were used at the station to meet customer needs.

Figure (IV-10): Design of the Gilbarco Veeder Root hydrogen dispenser

4. Final Design of the Station Structure :

The design occupies an area of 246**00 m^2**. The colours green, red and white, which are the colours of the Algerian flag, were chosen to make the station more representative of the country.

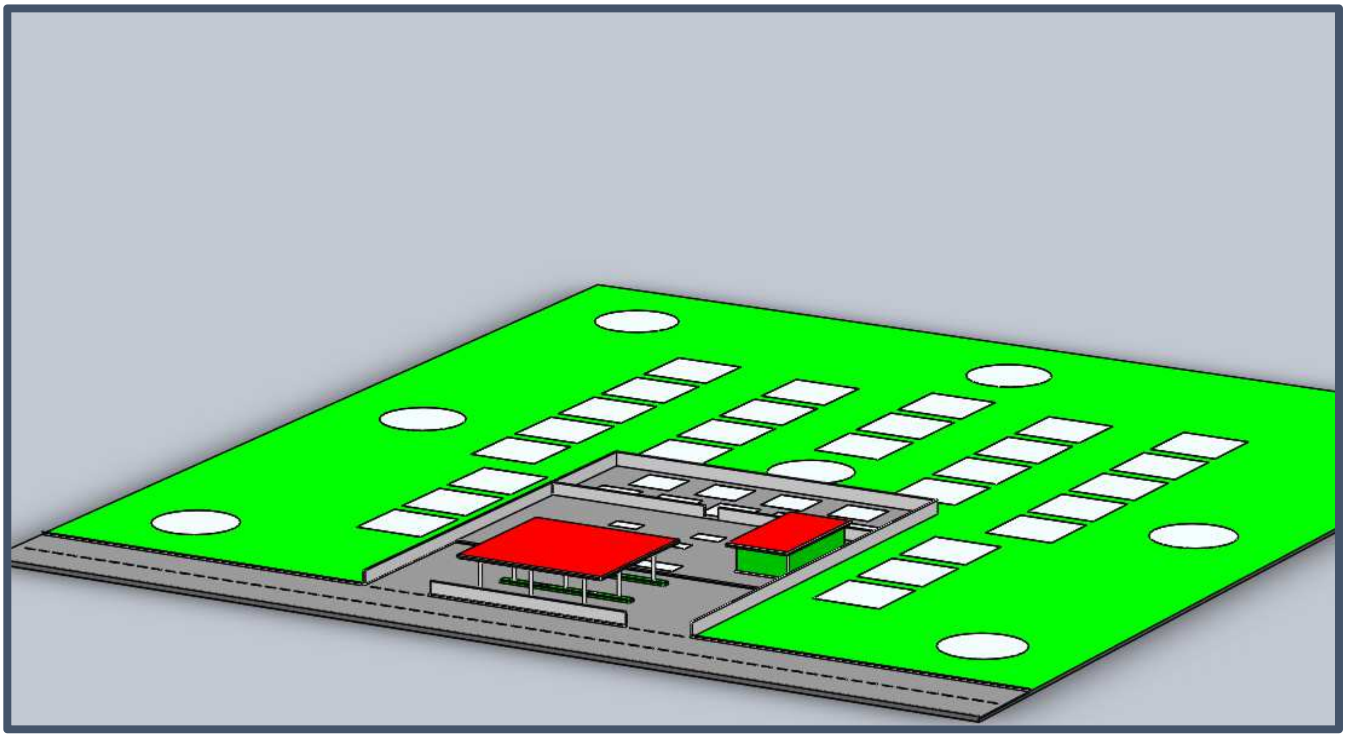
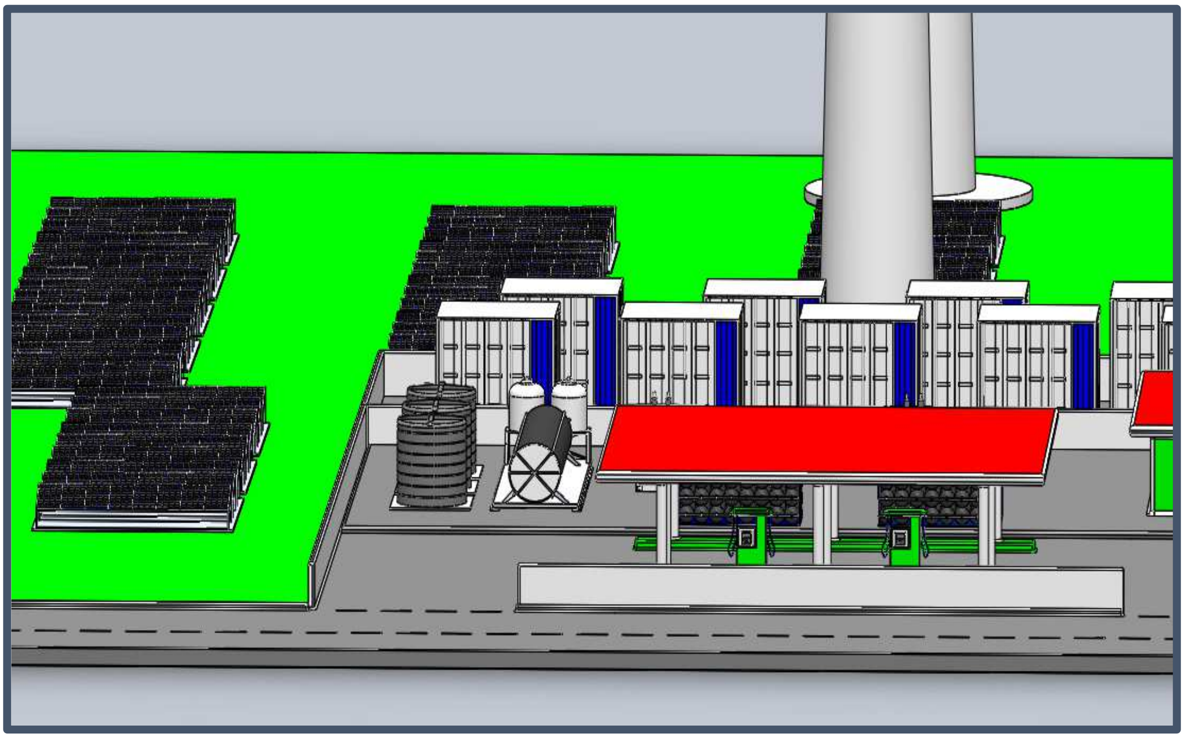
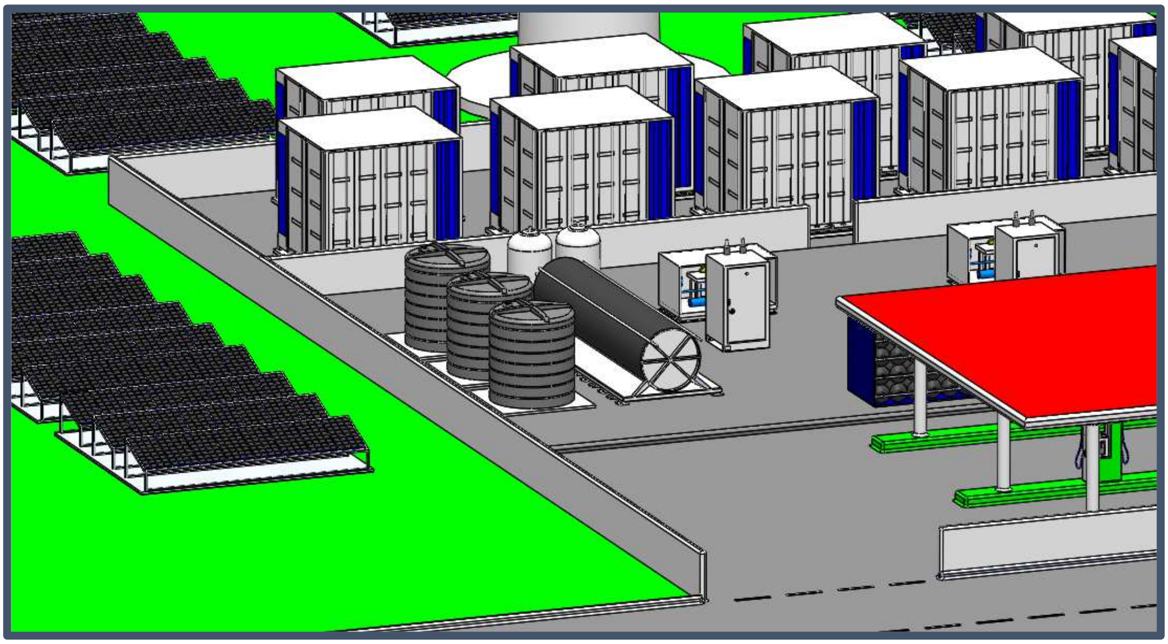


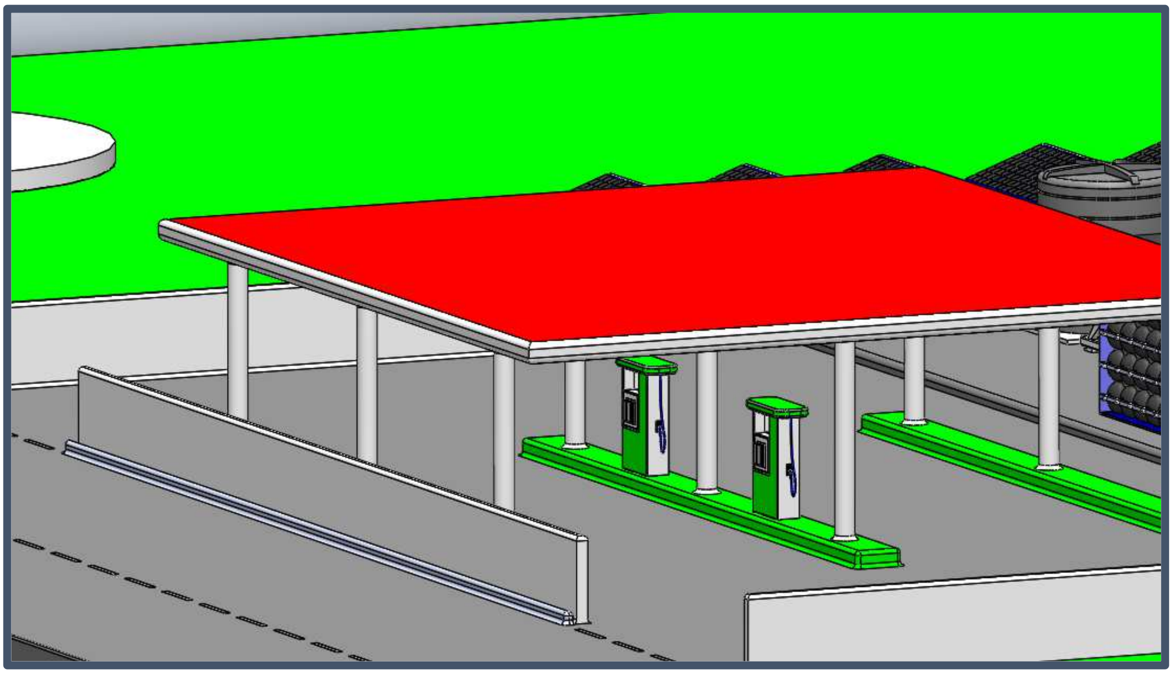
Figure (IV-11): Final Design of the Station Structure

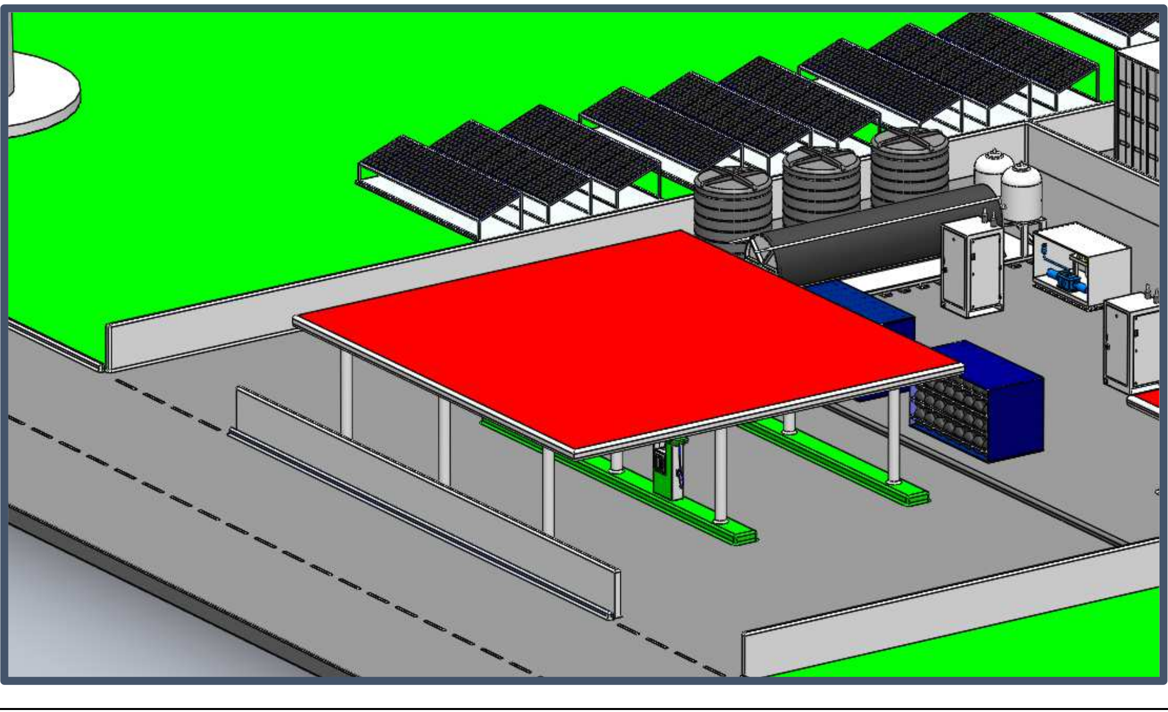
5. Final Design after assembly of Station Components :

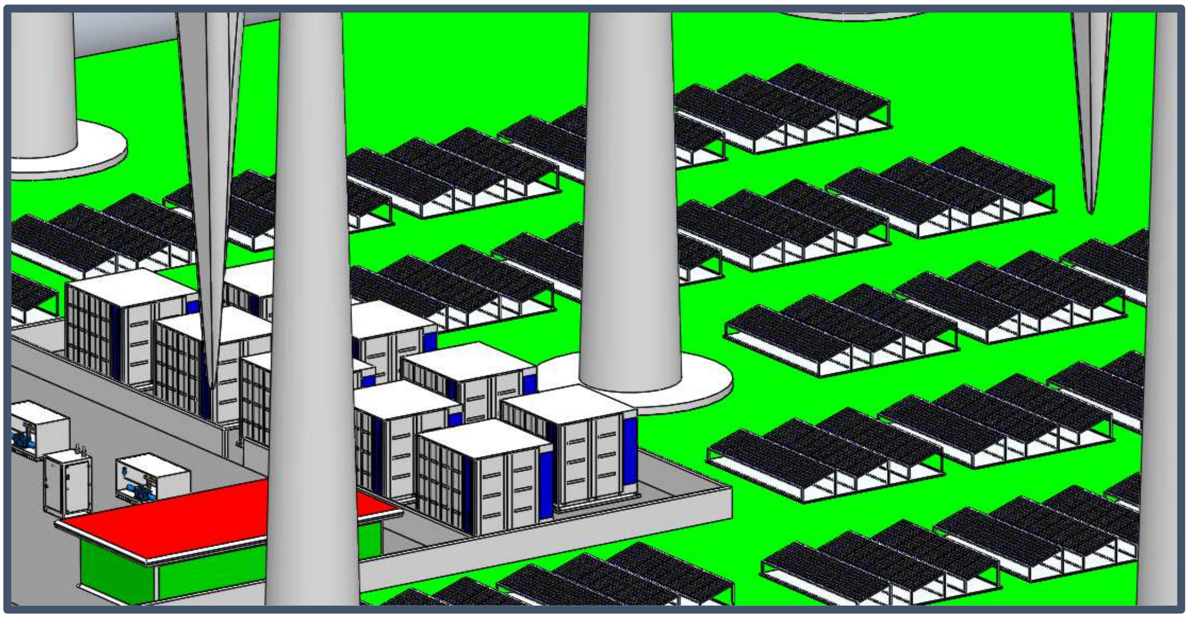
These are Screenshots of the finished station, taken from different angles after all its components have been assembled **:**

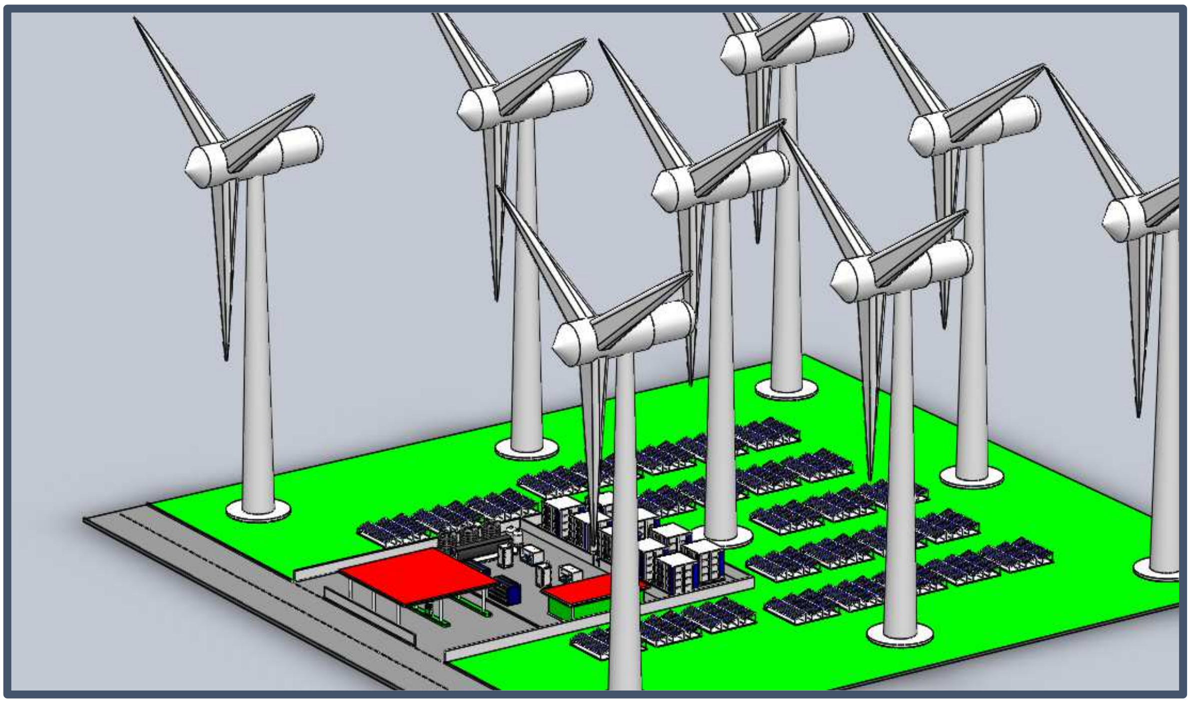


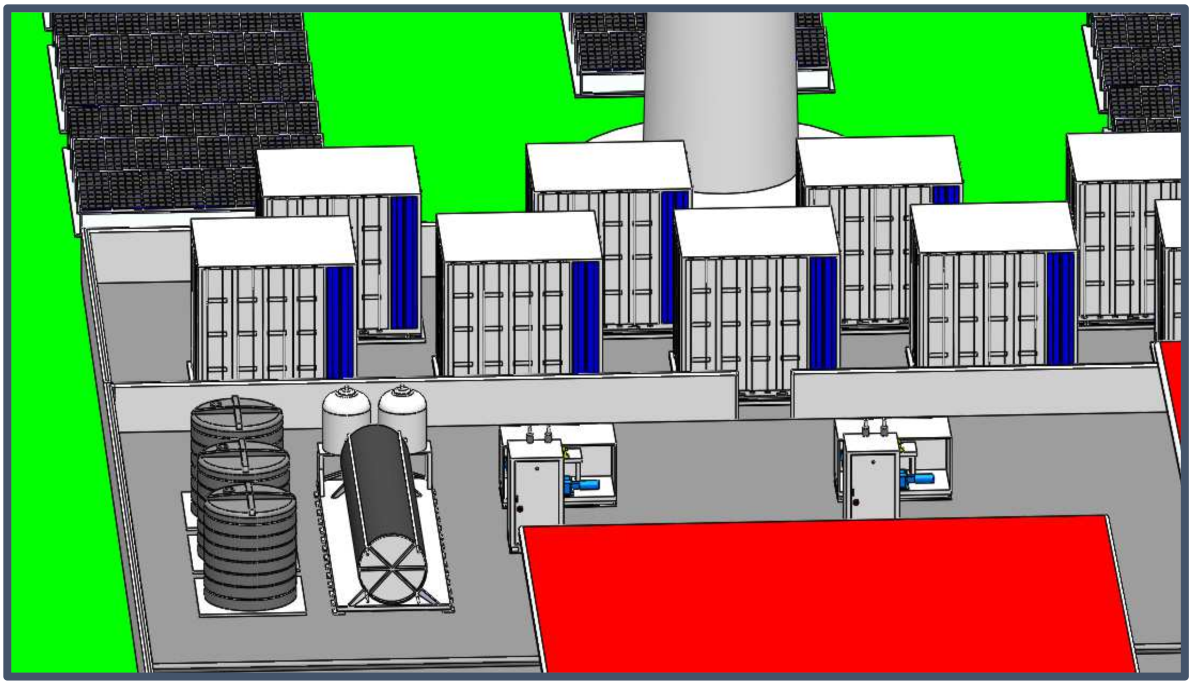












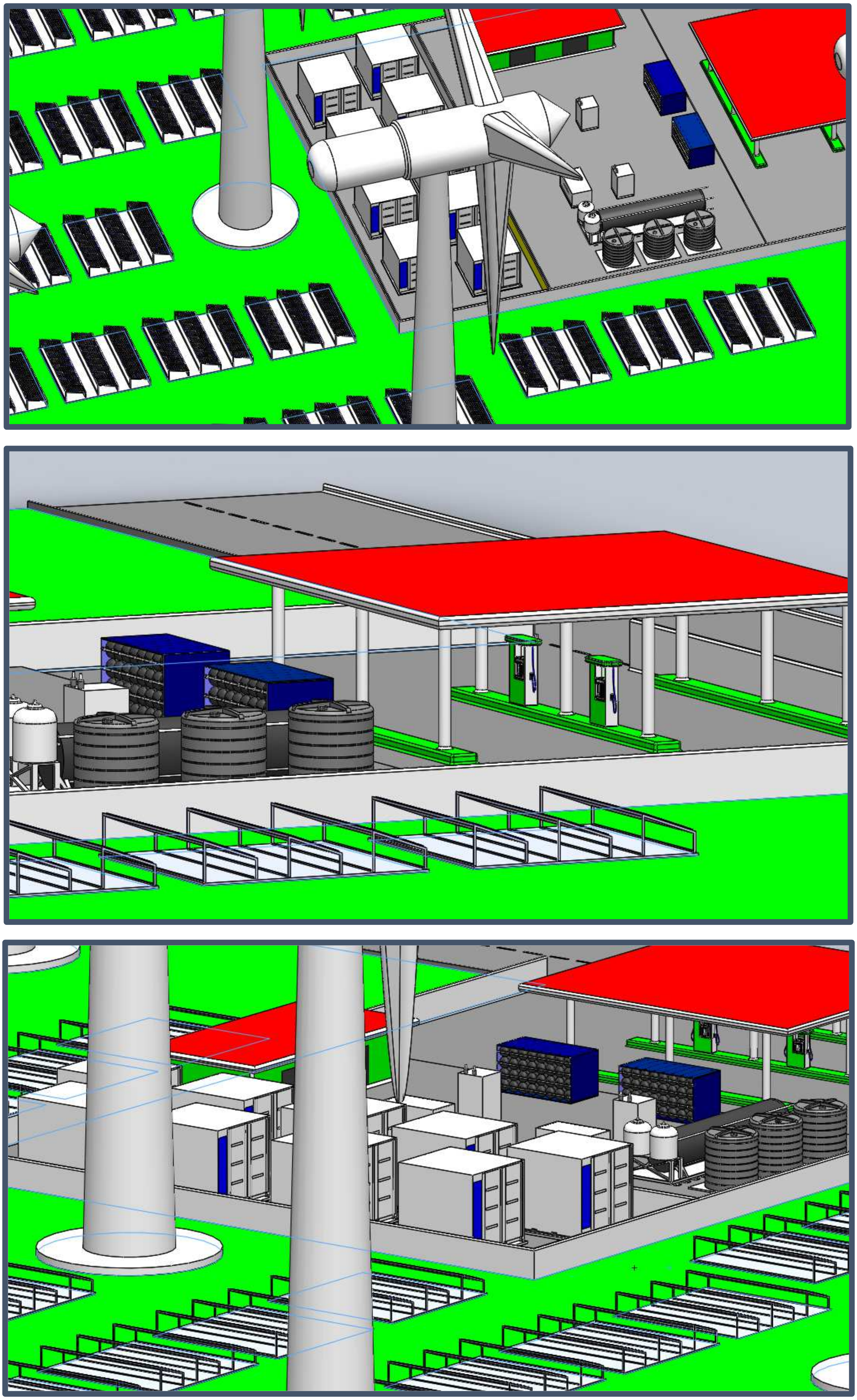


Figure (IV-12): Screenshots of the final design of the Algerian hydrogen station from different angles

6. Conclusion :

In this chapter, the integrated engineering design of a green hydrogen production system, based on renewable energy sources, has been presented and illustrated. The visual and structural aspects of each main component, from renewable energy generation units to hydrogen processing and storage systems, were emphasized through the inclusion of illustrative design images. This design confirms the feasibility of achieving an integrated and efficient system and represents the technical foundation upon which the detailed calculations and analyses presented in the previous chapter were built. This design paves the way for the practical potential of implementing green hydrogen solutions as a major contributor to a sustainable energy future.

Chapter 05:

Station Maintenance in the Context of Artificial Intelligence Developments

1. Introduction :

The field of maintenance is undergoing a radical transformation with rapid developments in artificial intelligence and robotics, with smart maintenance becoming the cornerstone of improving operational efficiency and minimising costs. This chapter is a comprehensive exploration of the role of AI in modernising hydrogen plant maintenance, from traditional methods to smart, data-driven solutions and advanced sensors. We will look at how these technologies can enhance safety, reduce unexpected failures, and improve overall plant performance.

2. Maintenance in the Age of Artificial Intelligence :

Industrial maintenance systems are undergoing a dramatic shift from traditional techniques to predictive and preventive maintenance enabled by the rapid advancement of artificial intelligence (AI) and robotics. A Siemens 2024 report found that unexpected equipment downtime costs major companies up to $1.4 trillion annually. As a result, there is a growing need to deploy intelligent maintenance solutions to minimise downtime and increase operational efficiency. [29]

2.1. Predictive Maintenance and Artificial Intelligence :

Predictive maintenance uses performance data collected by sensors on industrial machinery to identify problems before they happen. Large companies such as Amazon and IBM have been using the technology for years. Today, startups like Aquant are using artificial intelligence-based algorithms to improve predictive accuracy and minimise false alarms. These systems analyse sensor data and historical records to make accurate suggestions about when and what type of maintenance is needed, helping companies such as Coca-Cola and HP save up to 23% on service costs. [29]

2.2. The Role of Robotics in Inspection and Maintenance :

Gecko Robotics is a leading example of the use of intelligent robots in maintenance. The company has developed wall-climbing robots equipped with advanced sensors and high-resolution cameras to inspect critical infrastructure such as dams, power plants and pipelines. Gecko's AI platform analyses the collected data to detect corrosion and cracks early, enabling proactive maintenance before failures occur. [29]

2.3. Generative AI to Support Technicians :

Companies such as Waites Sensor Technologies have integrated Large Language Models (LLMs) into their systems, allowing technicians to interact directly with maintenance platforms using natural language queries such as "What are the most failure-prone machines ?". This simplifies access to information and speeds up decision-making without having to navigate complex dashboards. [29]

2.4. Challenges of Adopting Smart Maintenance :

Despite its benefits, AI-driven maintenance faces several challenges :

- High initial cost of installing smart sensors and upgrading existing systems.
- Difficulty integrating with legacy infrastructure and disparate data sources.
- Skills gaps in traditional maintenance teams unfamiliar with AI tools.
- Concerns about job displacement, even though the technology is intended to support human technicians, not replace them.

However, industry experts agree that companies that invest in AI-assisted maintenance can gain a significant competitive advantage and improve their long-term operational performance. [29]

3. Maintenance Plan for Hydrogen Refuelling Stations :

Regular and methodical maintenance is a key component in ensuring the safe and effective operation of hydrogen refuelling stations. These stations have rigorous protocols in place to reduce the risks associated with hydrogen's properties, such as high flammability and leakage. With an emphasis on safety and compliance with local and global regulations, this plan describes the critical actions and protocols for the maintenance of hydrogen refuelling equipment. [30]

Section	Key Steps/Procedures	Details/Requirements
Initial Preparation	Isolation of Energy Sources (Lockout/Tagout – LOTO)	o Secure all energy sources (electrical, pressure) using the LOTO system to prevent accidental activation. o Compliance with safety standards such as OSHA 1910.147 or equivalent local regulations.
	Purging Hydrogen from the System	o Remove hydrogen from equipment using an inert gas (e.g., nitrogen) before starting work. o Measure residual hydrogen concentration to ensure it is reduced to a safe level (below 1% per standards).
Written Procedures	Confined Space Entry	o Verify adequate ventilation and absence of hazardous gases before entry. o Use continuous gas monitoring devices.

	Verifying Equipment Readiness for Maintenance	o Inspect pressure, temperature, and hydrogen concentration before work begins. o Document all steps in maintenance reports.
	Work Permits	o Issue permits specifying tasks, hazards, and emergency procedures. o Hot Work Permit : ▪ Require extinguishing nearby ignition sources and availability of fire extinguishers. ▪ Compliance with NFPA standards or equivalents.
Job Safety Analysis	Break Down Tasks	o Define each activity (e.g., valve inspection, pipe replacement).
	Identify Hazards	o Such as hydrogen leaks, high-pressure exposure, or sparks.
	Implement Controls	o Use spark-resistant tools, protective gear, and worker training.
	Documentation	o Use a JSA form to record findings and share with the team.
Training and Awareness	Train workers on	o LOTO and purging procedures. o Handling leak detection devices. o Emergency response plans for fires or leaks.
Continuous Review and Improvement	Incident Review	o Analyze past incidents to improve procedures.
	Periodic Inspections	o Monthly checks of equipment integrity (e.g., fittings, pipes).
	Compliance with Hydrogen Standards	o Such as ISO 16111 or local regulations.

Table (V-01): Hydrogen Stations Safety and Maintenance Plan [30]

4. Maintenance of station components :

4.1. Solar Panel Maintenance :

Solar panels represent a long-term investment that requires simple, yet consistent, maintenance to ensure optimal performance and energy savings. This involves regular cleaning to combat efficiency reduction from dust and debris, continuous performance monitoring to detect drops in energy production, and annual expert inspections for potential faults like damaged cables or inverters. Consideration of location and climate, such as increased dust in desert areas or snow removal in snowy regions, is crucial for effective maintenance. Proactive measures, such as avoiding walking on panels and inspecting the system after severe storms, along with diligent record-keeping, help maximize their lifespan. [31]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Regular Cleaning	Spray panels with a hose or bucket of water ; avoid using harsh chemicals or abrasive brushes.	At least twice a year; more frequently in dusty areas or where there is low rainfall.	Accumulation of dust, leaves, or snow reduces light absorption efficiency.
Continuous Performance Monitoring	Use monitoring applications (such as those provided by installation companies) to track the energy production of each panel.	Continuously	Pay attention to sudden drops in productivity, as these may indicate dirt build-up or a technical fault.
Annual Expert Inspection	Conduct a comprehensive annual inspection to detect potential faults, such as damaged cables or inverters.	Annually	Recommended to detect potential faults not visible during routine checks.
Post-Storm Inspection	Inspect the system after severe storms.	As needed (after severe storms)	Check for physical damage to panels, mounting, or wiring.
Record Keeping	Keep a record of all maintenance and inspections.	Ongoing	Provides a history of maintenance activities for troubleshooting and planning.

Table (V-02): Solar Panels Maintenance Schedule [31]

4.2. Wind Turbine Maintenance:

Wind turbines, a vital component in hydrogen refueling stations, require meticulous maintenance to ensure their continuous performance and efficiency. Basic maintenance involves regularly inspecting blades for cracks, wear, or damage caused by storms, sand, or lightning strikes, and cleaning them to remove contaminants that reduce pick-up efficiency. It also includes inspecting the gearbox for wear and oil leaks, applying periodic lubrication to reduce friction, monitoring the generator for electrical or mechanical failures affecting power conversion, and inspecting the tower and foundations for cracks in the metal structure or concrete foundation. Both preventive maintenance, through periodic inspection, oil changes, and component cleaning, and predictive maintenance, utilizing sensors to monitor vibrations, temperatures, and the performance of electrical components, are effective strategies. These procedures aim to extend the lifespan of turbines and prevent damages resulting from environmental factors like lightning strikes or sand erosion, or operational errors such as exposing the turbine to wind speeds exceeding design specifications or neglecting to balance blades after partial damage. It is recommended to choose installation sites away from areas prone to sandstorms or lightning strikes, train teams to use smart monitoring systems, and sign maintenance contracts with specialized companies to minimize long-term costs. [32]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Blade Inspection	Look for cracks, wear, or damage caused by storms, sand, or lightning strikes. Clean the blades to remove dust and other contaminants that reduce pick-up efficiency.	Periodic	Essential for maintaining wind capture efficiency and preventing failures.
Gearbox Inspection	Check for gear wear and oil leaks. Apply periodic lubrication to reduce friction.	Periodic	Ensures smooth operation and prevents mechanical failures.
Generator Monitoring	Detect electrical or mechanical failures affecting power conversion.	Continuous	Identifies problems early and prevents shutdowns.
Tower and Foundation Inspection	Ensure that there are no cracks in the metal structure or concrete foundation.	Periodic	Ensures structural stability and prevents safety risks.
Preventive Maintenance	Periodic inspection, oil changes, and cleaning of components.	Periodic (according to a defined schedule)	Reduces the likelihood of sudden failures and extends component life.
Predictive Maintenance	Use sensors to monitor vibrations, temperatures, and performance of electrical components.	Continuous	Predicts problems before they occur, allowing for targeted maintenance.

Damage Management (Causes of Damage)	Consider environmental factors (lightning strikes, sand erosion) and operational errors (exposing the turbine to excessive wind speeds, neglecting to balance blades after partial damage).	As needed (after events)	Helps understand the causes of damage and prevent recurrence.
Maximize Lifespan	Choose installation sites away from areas prone to sandstorms or lightning strikes. Train teams to use smart monitoring systems. Sign maintenance contracts with specialized companies to minimize long-term costs.	Ongoing	Ensures operational continuity and reduces long-term costs.

Table (V-03): Wind Turbine Maintenance Schedule [32]

4.3. Renewable Energy Storage Battery Maintenance :

Maintaining renewable energy storage batteries is crucial for ensuring optimum performance, extending system life, preventing safety hazards, and maintaining energy efficiency. Basic maintenance involves regular visual inspections to check for damage, corrosion, or signs of overheating. Cleaning includes removing dust and debris and cleaning terminals to prevent corrosion. Professional maintenance encompasses performance testing and system diagnostics, while minor repairs involve tightening loose connections and replacing damaged components. The service frequency for these tasks is typically monthly for basic visual checks, quarterly for cleaning, and yearly for professional inspections. Additionally, it is vital to avoid overcharging, maintain good ventilation, monitor temperature, and use quality components to maximize the lifespan and safe operation of the battery storage system. [33]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Visual Inspections	Check for damage, corrosion, or signs of overheating.	Monthly	Crucial for early detection of physical issues.
Cleaning	Remove dust and debris. Clean terminals to prevent corrosion.	Quarterly	Ensures proper electrical contact and prevents degradation.
Professional Maintenance	Conduct performance testing and system diagnostics.	Yearly	Provides in-depth assessment and optimization of the system.

Minor Repairs	Tighten loose connections and replace damaged components.	As needed	Addresses small issues before they escalate into major problems.
Avoid Overcharging	Ensure the battery system is not overcharged.	Continuous	Overcharging can significantly reduce battery lifespan and pose safety risks.
Maintain Good Ventilation	Ensure adequate ventilation around the battery storage area.	Continuous	Prevents heat buildup, which can degrade battery performance and safety.
Monitor Temperature	Regularly monitor the operating temperature of the batteries.	Continuous	Extreme temperatures can negatively impact battery efficiency and longevity.
Use Quality Components	Ensure that all components used in the battery system are of high quality.	Initial installation & replacements	Contributes to overall system reliability and safety.

Table (V-04): Renewable Energy Storage Battery Maintenance Schedule [33]

4.4. Deionized Water Tanks Maintenance:

For systems utilizing deionized water, the maintenance of plastic storage containers is paramount to ensure water purity, prevent contamination, maintain tank integrity, and extend its operational lifespan. Maintenance primarily focuses on regular cleaning and sanitization to prevent the accumulation of bacteria and contaminants. This is complemented by routine inspection for leaks and cracks in the tank's structure. It's crucial to inspect valves and connections to ensure proper functioning and prevent any leakage. A vital aspect for plastic tanks is protection from direct sunlight, which significantly helps in prolonging their life by preventing material degradation. For regions with low temperatures, preparing the tank for winter involves draining and insulating it to prevent freezing. It is recommended to perform a comprehensive tank inspection at least twice a year. You must pay close attention to changes in water color, odor, or the presence of sediment, as these are indicators that immediate cleaning is required. Plastic tanks, being more susceptible to damage than concrete, also require protection from sharp or heavy objects and ensuring adequate ventilation to prevent pressure buildup. [34]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Cleaning and Sanitization	Clean and sanitize the inside of the tank using a mild cleaner and brush,	At least once a year	Essential to prevent the accumulation of bacteria and contaminants that could affect deionized water purity.

	then rinse thoroughly with clean water.		
Leak and Crack Inspection	Regularly inspect the tank for any leaks or cracks in the structure, and repair them immediately upon detection.	Every six months (or more frequently depending on usage/conditions)	Prevents water loss and degradation of water quality, especially crucial for pure water.
Valves and Connections Check	Ensure all tank valves and connections are functioning correctly, and replace any showing signs of wear or damage.	Every six months	Prevents leaks and ensures proper control of water flow.
Protection from Sunlight	Cover the tank with a shade cloth or paint it with UV-resistant paint if it's exposed to direct sunlight.	Continuous	Extends the lifespan of the plastic tank by preventing material degradation due to UV exposure.
Winter Preparation	Completely drain the tank and disconnect all pipes and fittings before covering it with an insulating blanket in cold regions.	Before freezing temperatures set in	Prevents water from freezing and damaging the tank structure.
Monitoring System Check (if applicable)	Verify the proper functioning of any water monitoring systems (e.g., purity level, temperature).	Regularly	Ensures the deionized water quality is maintained.
Physical Protection	Keep the plastic tank away from sharp or heavy objects that could cause damage.	Continuous	Prevents punctures or structural damage to the tank.
Ventilation Check	Ensure the plastic tank has adequate ventilation	Regularly	Essential for safe operation and to prevent deformation due to pressure changes.

	openings to prevent pressure buildup.		
Indicators for Cleaning	Note any change in water color (dark/cloudy), a foul odor from the water, or the presence of sediment at the bottom of the tank.	Upon observation	These are signs of water contamination and accumulation of bacteria/germs, indicating immediate cleaning is needed.

Table (V-05): Deionized Water Tanks Maintenance Schedule [34]

4.5. Electrolyser Maintenance :

Maintenance of electrolysers requires a thorough understanding of their operating characteristics and associated hazards to ensure efficient and safe hydrogen production while minimizing the risk of accidents. A major safety concern is hydrogen-oxygen gas crossover, which can lead to the formation of flammable mixtures under conditions such as startup and shutdown. Strict adherence to manufacturers' guidelines for system operation and maintenance of safety devices like gas detectors and recombiners is essential. Electrolysis stacks can retain electrical charge after shutdown, posing an arcing or discharge risk during maintenance, thus technicians must ensure full discharge before work. Installation in well-ventilated, non-classified areas away from ignition sources, along with the use of certified components, is crucial for safety and code compliance. Furthermore, waste process streams containing dissolved hydrogen or oxygen must be discharged to open, ventilated areas to prevent gas accumulation and hazardous incidents. Oxygen itself poses serious fire hazards, especially under pressure or in enriched environments, necessitating proper material selection and venting away from ignition sources. In emergencies, the system must automatically shut down hydrogen production, isolate storage, and safely vent gases while maintaining ventilation. [30]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Operational Safety & Gas Crossover Prevention	Adhere strictly to manufacturers' guidelines for system operation. Maintain safety devices such as gas detectors and recombiners.	Continuous operation & regular checks	Prevents hydrogen-oxygen gas crossover and formation of flammable mixtures, especially during startup/shutdown.
Electrical Maintenance & Discharge Verification	Technicians must check that the electrolysis stack is fully discharged using appropriate measuring tools and protective	Before any maintenance work	Electrolysis stacks can retain electrical charge after shutdown, posing arcing/discharge risk.

	equipment before starting maintenance.		
Installation Considerations	Ensure electrolysers are installed in well-ventilated, non-classified areas away from ignition sources. Use certified components.	Initial installation	Enhances safety and code compliance.
Handling Waste Process Streams	Discharge liquid waste containing dissolved hydrogen or oxygen to open, ventilated areas. Avoid connecting drains to closed or shared systems.	Continuous operation & system design	Prevents gas accumulation and hazardous incidents.
Oxygen Hazard Mitigation	Proper material selection and venting away from ignition sources.	Continuous operation & system design	Oxygen poses serious fire hazards, especially under pressure or in enriched environments.
Safe System Shutdown Procedures	In emergencies (e.g., ventilation failure, gas leak), the system must automatically shut down hydrogen production, isolate storage, and safely vent gases while keeping ventilation active.	Emergency response	Crucial for preventing escalation of hazardous situations.

Table (V-06): Electrolyser Maintenance Schedule [30]

4.6. Hydrogen Diaphragm Compressor Maintenance :

Maintenance of hydrogen diaphragm compressors is critical to the safe and efficient operation of hydrogen systems. Maintenance schedules are typically based on operating hours and time intervals, encompassing start-up inspections, periodic maintenance at regular intervals, and major mechanical maintenance after a certain number of years or under severe operating conditions. Procedures for these maintenance types involve filter checks, component cleaning, oil changes, replacement of certai parts, and inspection of wear parts. Due to the nature of hydrogen gas, special considerations during maintenance include ensuring the integrity of seals and gaskets to prevent hydrogen leakage, using hydrogen-compatible materials to avoid corrosion and deterioration, and regularly inspecting components for cracking, which can result from hydrogen embrittlement. A list of required spare parts, such as seals, gaskets, filters, check valves, and diaphragms, is also crucial for effective maintenance. [35]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Start-up Inspection	Filter checks, component cleaning, and oil changes.	On first start-up	Ensures proper initial operation.
Periodic Maintenance	Component checks, replacement of certain parts, valve checks, and parts cleaning.	Regular intervals based on operating hours or years	Maintains ongoing efficiency and prevents minor issues from escalating.
Major Mechanical Maintenance	Replacement of major parts such as bearings and rings, and inspection of wear parts.	After a certain number of years or under severe operating conditions	Addresses significant wear and tear for long-term reliability.
Leak Prevention	Ensure the integrity of seals and gaskets to prevent hydrogen leakage.	Ongoing, during inspections	Critical due to the flammability and leakage properties of hydrogen.
Compatible Materials Usage	Use hydrogen-compatible materials to avoid corrosion and deterioration.	During replacements/repairs	Prevents material degradation caused by hydrogen.
Crack Inspection	Regularly inspect components for cracking, which can result from hydrogen embrittlement.	During inspections	Hydrogen embrittlement can compromise component integrity.
Spare Parts Management	Ensure availability of spare parts (seals, gaskets, filters, check valves, diaphragms).	Ongoing	Essential for timely replacements during maintenance.

Table (V-07): Hydrogen Diaphragm Compressor Maintenance Schedule [35]

4.7. Hydrogen Cooler Maintenance :

Maintaining hydrogen coolers is vital for ensuring efficient and safe operation of hydrogen refueling stations by effectively removing heat generated during the compression process. Without proper cooling, the hydrogen could reach dangerously high temperatures, impacting safety and system performance.

Regular maintenance typically involves several key area cleaning, checking for leaks, and inspecting components. Routine cleaning of the heat exchanger fins is crucial to prevent dust and debris buildup, which can significantly reduce cooling efficiency. Frequent checks for hydrogen or coolant leaks are essential due to safety concerns associated with hydrogen and the need to maintain optimal coolant levels. Furthermore, inspecting components like fans, pumps, and valves for wear, damage, or malfunction helps prevent system downtime and ensures consistent cooling. Following the manufacturer's specific guidelines for maintenance is paramount, as different cooler designs may have unique requirements. Proactive maintenance ensures the cooler operates at peak efficiency, contributes to overall system reliability, and helps mitigate potential hazards associated with high-temperature hydrogen. [36]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Cleaning Heat Exchanger Fins	Remove dust, debris, and any obstructions from the heat exchanger fins. This can be done with compressed air, a soft brush, or water, depending on the manufacturer's recommendations.	Regularly (e.g., monthly or quarterly, depending on environmental conditions)	Prevents reduction in cooling efficiency due to buildup.
Leak Checks	Inspect all connections, hoses, and pipes for any signs of hydrogen or coolant leaks. Use appropriate leak detection methods for hydrogen.	Frequently (e.g., weekly or daily, depending on operational demands)	Crucial for safety due to hydrogen's flammability and to maintain system performance.
Fan Inspection	Check cooling fans for proper operation, unusual noises, vibration, and blade integrity. Ensure they are free from obstructions.	Regularly (e.g., monthly)	Ensures adequate airflow for heat dissipation.
Pump Inspection (if applicable)	For liquid-cooled systems, inspect the coolant pump for proper operation, leaks, and signs of wear.	Regularly (e.g., monthly or quarterly)	Ensures effective circulation of the cooling medium.

Valve and Sensor Checks	Inspect all valves for proper functioning (opening/closing) and check sensors for accurate readings of temperature and pressure.	Periodically (e.g., quarterly)	Ensures precise control over the cooling process and system safety.
Coolant Level and Quality Check (for liquid-cooled systems)	Monitor coolant levels and quality; replenish or replace as needed according to manufacturer specifications.	Periodically (e.g., quarterly or annually)	Maintains optimal heat transfer properties and prevents corrosion.
Adherence to Manufacturer Guidelines	Always follow the specific maintenance schedule and procedures outlined in the hydrogen cooler's manual.	Continuous	Different models and designs may have unique maintenance requirements.

Table (V-08): Hydrogen Cooler Maintenance Schedule [36]

4.8. Maintenance of Hydrogen Storage Containers :

Hydrogen storage containers are a critical component in any hydrogen system, and their maintenance is paramount for ensuring safety, preventing leaks, and maintaining the integrity of the stored hydrogen. The primary focus of maintenance involves routine inspections to detect any signs of physical damage, corrosion, or deformation. Given the high pressures involved and the flammability of hydrogen, leak detection is a continuous and crucial task, requiring the use of specialized detectors and regular pressure checks. Furthermore, periodic re-qualification and hydrostatic testing are essential to comply with safety standards and ensure the structural integrity of the containers over time. Material compatibility is also a key consideration; using materials resistant to hydrogen embrittlement and corrosion is vital to prevent long-term degradation. Any internal or external coating systems should also be inspected for integrity. Additionally, ensuring proper ventilation in storage areas helps mitigate risks associated with potential leaks. A robust maintenance plan, combining visual inspections, advanced leak detection, and scheduled certifications, is indispensable for the safe and reliable operation of hydrogen storage facilities. [30]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Visual Inspection	Check for physical damage, dents, cracks, corrosion, deformation, or any signs of wear on the container's exterior and structural	Regularly (e.g., monthly or quarterly)	Early detection of physical issues is crucial for safety and integrity.

	supports. Inspect external coating systems.		
Leak Detection	Use specialized hydrogen leak detectors to check all connections, valves, and welds. Monitor pressure readings for any unexplained drops.	Continuously (via sensors) & periodically (manual checks, e.g., weekly)	Hydrogen is highly flammable; preventing leaks is paramount.
Pressure Relief Device (PRD) Inspection	Verify that PRDs are not corroded or blocked and are functioning correctly. They are vital for preventing over-pressurization.	Annually or as per manufacturer's guidelines	Ensures safe release of pressure in case of overpressure.
Valve and Fitting Inspection	Check all valves, gauges, and fittings for proper operation, signs of wear, or leaks.	Regularly (e.g., quarterly)	Ensures precise control and containment of hydrogen.
Re-qualification and Hydrostatic Testing	Periodically re-qualify the containers according to national and international safety standards (e.g., DOT, ISO). This often involves hydrostatic testing.	As per regulatory requirements (e.g., every 5-10 years)	Ensures structural integrity under pressure over the container's lifespan.
Material Integrity Check	Pay attention to signs of hydrogen embrittlement or material degradation, especially in critical stress areas.	During re-qualification and major inspections	Hydrogen can affect certain materials over time, leading to embrittlement.
Ventilation System Check	Ensure the storage area has adequate and functioning ventilation to disperse any potential hydrogen leaks.	Regularly (e.g., monthly)	Prevents accumulation of hydrogen, reducing explosion risk.
Documentation and Certification Review	Maintain updated records of all inspections, maintenance activities, and re-qualification certificates.	Ongoing	Ensures compliance and traceability of maintenance history.

Table (V-09): Maintenance of Hydrogen Storage Containers Schedule [30]

4.9. Hydrogen Dispensers Maintenance :

Hydrogen dispensers are the interface between the hydrogen station and the vehicle, and their proper maintenance is paramount for safety, accurate fueling, and operational reliability. Maintenance of these units focuses heavily on preventing leaks, ensuring precise metering, and verifying the integrity of all components that come into contact with high-pressure hydrogen. This includes routine visual inspections for signs of wear, damage, or leaks around hoses, nozzles, and connections. Leak detection is a continuous and critical process, often supported by integrated sensors, but also requiring manual checks. Calibration of the flow meter is essential to ensure accurate hydrogen dispensing for billing and safety. Regular inspection and replacement of filters prevent contamination and maintain flow rates. Given the high pressures and flammability of hydrogen, all maintenance activities must strictly adhere to safety protocols, including depressurization of lines before servicing, proper lockout/tagout procedures, and the use of specialized tools and personal protective equipment. A detailed maintenance log should be kept for all checks, repairs, and calibrations to ensure compliance and traceability. [37]

Maintenance Task	Description	Frequency	Key Considerations/Notes
Visual Inspection	Check dispenser body, hoses, nozzles, breakaways, and connections for physical damage, wear, kinks, cracks, or signs of hydrogen leakage (e.g., frosting, abnormal sounds).	Daily/Weekly	Early detection of physical issues is crucial for safety and operational continuity.
Leak Detection	Use portable hydrogen leak detectors to check all potential leak points. Monitor built-in leak detection systems if available.	Weekly (manual checks)	Critical for safety due to hydrogen's flammability and stealthy nature of leaks.
Flow Meter Calibration	Verify the accuracy of the flow meter against a certified standard. Adjust if necessary to	Annually	Ensures accurate billing and proper fueling.

	ensure precise dispensing.		
Filter Inspection/Replacement	Check filters within the dispenser for contamination or clogging. Replace as per manufacturer's guidelines or if flow rate is impacted.	Quarterly or as per manufacturer's recommendations	Prevents contaminants from entering the vehicle and maintains proper flow.
Hose and Nozzle Functionality	Test the functionality of the nozzle (e.g., proper engagement, disengagement) and inspect the integrity of the fueling hose. Check for wear on breakaway couplings.	Monthly	Ensures secure and efficient fueling process.
Pressure Gauge and Sensor Verification	Verify the accuracy of pressure gauges and other sensors. Calibrate or replace if readings are inconsistent.	Annually	Critical for monitoring system pressure and safe operation.
Safety Interlock Testing	Test all safety interlocks and emergency stop buttons to ensure they function correctly.	Quarterly	Ensures that the system can be safely shut down in an emergency.
Structural Integrity of Mounting	Inspect the dispenser's mounting to the island or foundation for stability, corrosion, or damage.	Annually	Ensures the dispenser is securely fixed and stable during operation.
Documentation	Maintain detailed records of all inspections, maintenance activities,	Ongoing	Essential for compliance, troubleshooting, and warranty purposes.

	repairs, and calibrations.		

Table (V-10): Hydrogen Dispensers Maintenance Schedule [37]

5. Hydrogen Station Maintenance from traditional techniques to Artificial Intelligence advances :

5.1. Traditional Maintenance of Hydrogen Stations :

Traditional hydrogen station maintenance methods rely on manual procedures and reactive responses, such as [37] :

- **Scheduled Maintenance :** Inspecting equipment on a fixed schedule, even when it's working normally, resulting in wasted time and resources.
- **Manual Inspection :** Relying on technical teams to identify faults through visual inspection or limited testing, which can miss subtle issues (such as small cracks or minor leaks).

High Costs : Reactive repairs after failures result in extended downtime and expensive fixes. [38]

Safety Risks : Hydrogen leaks (which are flammable) can go undetected until the next inspection, increasing the risk of accidents. [38]

5.2. How Artificial Intelligence Is Reshaping Station Maintenance :

Artificial Intelligence transforms maintenance from a routine task into a data-driven intelligent system by :

a) **Continuous monitoring with intelligent sensors [38] :**

- **Vibration sensors :** Detect small changes in the movement of motors or compressors to predict bearing failure.
- **Acoustic sensors :** Detect high frequency sounds caused by hydrogen leaks in pipelines.
- **Thermal cameras :** Take infrared images of electrical connections to prevent overheating.

Benefit : 24/7 equipment monitoring without human intervention.

b) **Integrated data analysis [38] :**

- Aggregates data from multiple sources (pressure, temperature, flow, vibration) into a central system.
- Use machine learning algorithms to uncover hidden correlations - for example, linking a rise in temperature to an increase in pressure as a warning of a clogged filter.

Benefit : Predicts failures days or weeks in advance.

c) Targeted proactive maintenance [38] :

- Sends customised alerts to maintenance teams specifying the likely type of failure and its exact location (e.g. "Cooling valve in unit 3 is expected to fail within 14 days").
- Recommends the optimum remedial action (replace component, clean filter, etc.) based on the severity of the fault.

Benefit : Reduces downtime by 30-50%.

d) Learning from historical records [38] :

- Analyses historical failure data to identify root causes (e.g. the effect of humidity on pipe corrosion).
- Automatically refines predictive models with each maintenance cycle.

Benefit : Prevents recurrence of similar problems.

e) Improved safety [38] :

- Detects small leaks in hydrogen tanks by analysing pressure and flow data.
- Monitors structural integrity using AI-processed satellite or drone imagery.

Benefits : Reduces the risk of accidents by up to 90%.

5.3. Practical examples [38] :

- **Germany :** Siemens used Artificial Intelligence systems to predict failures in electrolysers, reducing maintenance costs by 25%.
- **Storage projects :** Analysis of sensor data in large underground tanks prevents cracks caused by pressure fluctuations.
- **Oil and gas sector :** Companies such as Shell are applying similar Artificial Intelligence driven maintenance to shared pipeline networks, reducing emergency shutdowns by 20%.

6. Conclusion :

This chapter emphasises that the shift from traditional to AI enabled maintenance is not just an option, but a necessity to ensure the efficiency and safety of future hydrogen plants. By leveraging smart sensors and advanced data analysis, failures can be predicted before they occur and preventive actions can be identified with high accuracy. However, the success of these technologies requires investments in infrastructure and upskilling of technical teams. Practical examples from various industries show that AI can deliver significant cost savings and increased safety, making it a key pillar of modern maintenance strategies. Ultimately, this chapter is a call for the Algerian state to embrace these transformations and utilise their full potential to build a more sustainable and reliable infrastructure.

General Conclusion

The transition to a clean and low carbon energy system represents one of the greatest challenges of the modern era, with hydrogen especially green hydrogen being a pivotal element in this transformation. This thesis addresses the subject from multiple perspectives to present a comprehensive roadmap for the conception, design, and maintenance of a green hydrogen station that aligns with the Algerian context.

In Chapter One, the strategic importance of hydrogen at the global level was highlighted through an analysis of its properties and uses, a review of supportive policies and initiatives, and a focus on Algeria's potential in this field.

Chapter Two focused on translating the general needs of the project into precise technical requirements using functional analysis tools, thereby establishing the scientific and practical foundation for the station's design.

Chapter Three added a practical dimension to the study by providing realistic calculations, a detailed feasibility study, and an analysis of the technologies involved, demonstrating that the project is technically feasible.

Chapter Four serves as the field implementation of the previous chapters, embodying the proposed design of the station as an integrated entity.

Chapter Five brought a forward-looking perspective by introducing a modern maintenance approach based on artificial intelligence, contributing to enhanced performance, reduced failures, and reliable operation.

This study opens up wide prospects for future application, both academically and industrially. On one hand, the theoretical design can be transformed into a practical prototype to be tested in southern Algerian regions rich in renewable energy. The research can also be deepened through a comprehensive economic feasibility study and the expansion of the maintenance system to include artificial intelligence technologies. On the other hand, the project presents a real opportunity for the creation of start-ups within the framework of the national policy to support innovation in renewable energies, contributing to Algeria's objectives in the field of green hydrogen.

In conclusion, this thesis serves as a scientific and technical reference for the development of hydrogen projects in Algeria. It is an open call to researchers, engineers, and policymakers to unite their efforts and invest in this promising field, which can enhance national energy security and contribute to addressing climate change both nationally and globally.

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