

H2-B1: INTRODUCTION TO HYDROGEN ENERGY AND ENERGY TRANSITION

Learning Objectives

By the end of this chapter, learners should be able to:

- Explain hydrogen as an energy carrier
- Describe hydrogen's role in the clean energy transition
- Identify key hydrogen applications and global trends
- Differentiate between green, blue, and grey hydrogen
- Describe basic fuel cell operation
- Relate hydrogen solutions to West African energy challenges
- Identify simple local opportunities for hydrogen use

Glossary of Key Terms

- **Hydrogen (H₂):** A light gas used to store and release energy
- **Electrolysis:** Process of splitting water into hydrogen and oxygen using electricity
- **Fuel Cell:** Device that converts hydrogen into electricity and water
- **Green Hydrogen:** Hydrogen made using renewable energy (solar, wind)
- **Blue Hydrogen:** Hydrogen made from gas with carbon capture
- **Grey Hydrogen:** Hydrogen made from fossil fuels without carbon capture
- **Electrolyzer:** Machine used for electrolysis
- **Feedstock:** Raw material used to produce hydrogen
- **Energy Carrier:** A substance that stores and transports energy
- **Decarbonization:** Reducing carbon emissions from energy systems

CHAPTER ONE

AFRICAN ENERGY CHALLENGES AND ENERGY TRANSITION (H2-B1-1)

1.1.The Reality: Everyday Energy Struggles in West Africa

Across West Africa, energy challenges are part of daily life. Consider a welding workshop in Lagos or a cold storage facility in Accra. Frequent power outages disrupt operations for hours, or even days. To continue working, businesses rely on diesel generators (commonly called “gen” or “*I pass my neighbour*”). These generators are expensive to operate, noisy, and produce harmful emissions.

In rural areas of Senegal, northern Nigeria, and beyond, many households still depend on kerosene lamps, charcoal, or firewood for lighting and cooking. These energy sources are not only inefficient but also pose health and environmental risks. Electricity access varies across the region. Figures 1.1 (a) and (b), respectively, show the electricity access map and the percentage population with electricity access across West Africa. While Ghana has achieved relatively high access rates (over 80%), countries like Nigeria average around 70–74%, with much lower access in rural communities. Even where electricity is available, supply is often unreliable.



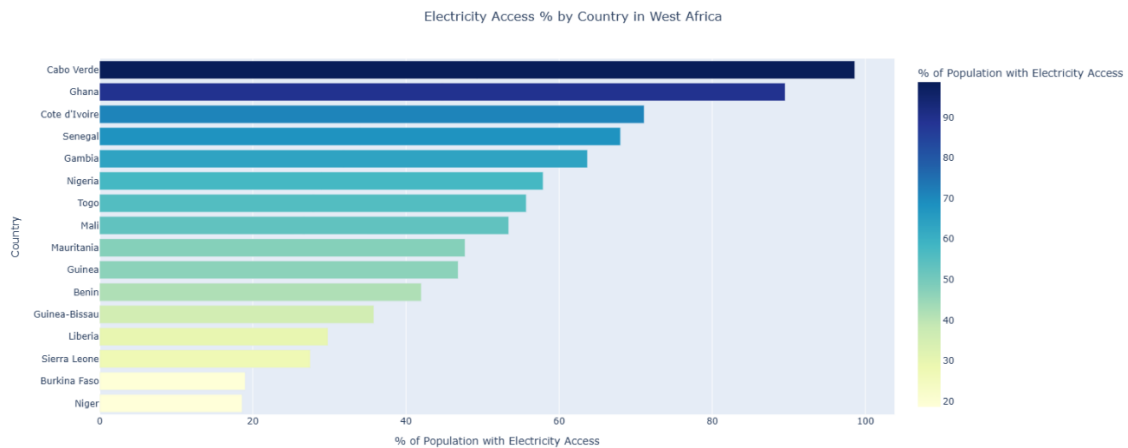


Figure 1.1 (a) Energy Access Map of West Africa b) Percentage Electricity Access by Country
These energy challenges have serious consequences:

- Businesses face high operating costs and reduced productivity
- Hospitals struggle to power essential equipment
- Students lack reliable lighting for studying
- Farmers cannot dependably run irrigation or storage systems

Heavy reliance on imported fossil fuels, especially diesel, also strains national economies and exposes countries to global price fluctuations.

Think It Through: How does unreliable electricity affect businesses or services in your community? What activities are most disrupted?

1.2. Why Energy Systems Fall Short?

West Africa's energy problems are complex and interconnected. Key challenges include:

- Infrastructure Limitations:** Many power systems rely on outdated equipment, weak transmission networks, and insufficient maintenance. This leads to frequent outages and unstable supply.
- Investment and Policy Barriers:** Energy infrastructure requires large financial investments. However, inconsistent policies and regulatory uncertainty often discourage investors.
- Skills Gap:** There is a shortage of technicians trained in modern energy systems such as renewable energy, hybrid systems, and emerging hydrogen technologies.
- Dependence on Fossil Fuels:** Many countries rely on diesel and natural gas for power generation. Others depend heavily on imported fuels, making them vulnerable to price shocks.

e) ***Climate and Environmental Pressures:*** The region faces increasing climate risks, including:

- Flooding in coastal cities like Lagos and Dakar
- Drought in Sahel regions
- Variability affecting hydropower and agriculture

These challenges damage infrastructure and reduce energy reliability.

The Role of Skilled Technicians: Across industries in Ghana, Nigeria, and Côte d'Ivoire, there is growing demand for technicians who can:

- Maintain solar and hybrid energy systems
- Diagnose grid instability
- Support emerging technologies like hydrogen storage and fuel cells

Developing these skills is critical for both job creation and energy system improvement.

1.3. The Need for Energy Transition

The current energy system is no longer sustainable. Continued dependence on fossil fuels leads to:

- High energy costs
- Environmental pollution
- Increased greenhouse gas emissions
- Vulnerability to global fuel markets

An **energy transition** is required, shifting from fossil-based systems to cleaner, more sustainable energy sources. For West Africa, this transition is essential for:

- Energy Security:* Using local energy resources instead of imports
- Economic Growth:* Supporting industries with reliable power
- Environmental Protection:* Reducing emissions and pollution
- Climate Resilience:* Building systems that can withstand extreme weather

Energy Transition Pathway:

- Fossil → Renewables → Hydrogen integration

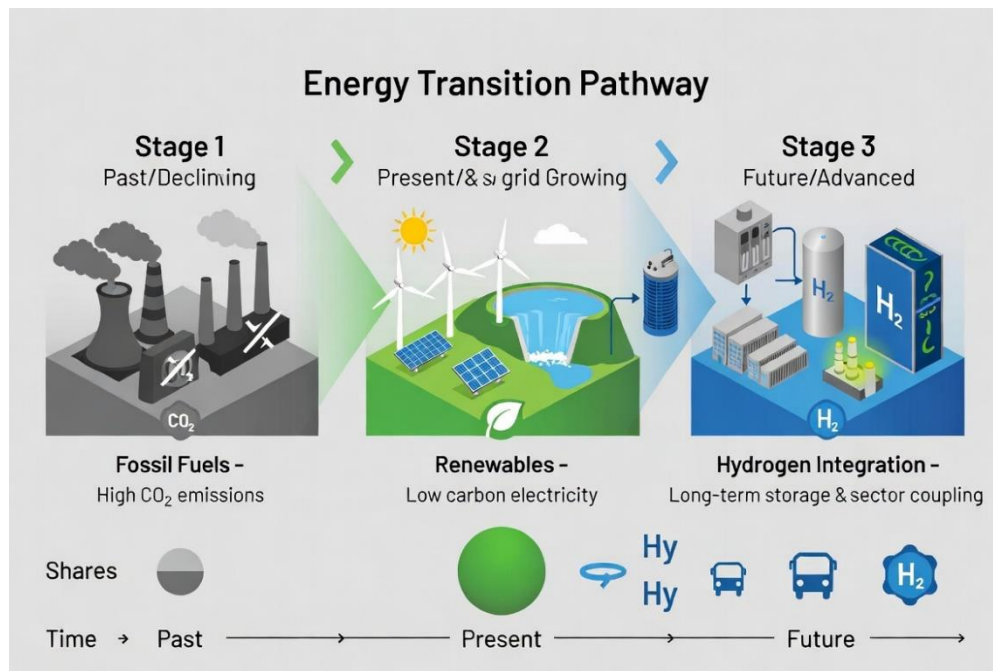


Figure 1.2 Energy transition pathway

1.3.1. Renewable Energy Potential

West Africa has strong renewable energy resources:

- **Solar energy** (abundant year-round sunlight)
- **Wind energy** (especially along coastal areas)
- **Hydropower** (existing dams such as Akosombo and Kainji)
- **Biomass** (agricultural residues like rice husks and cassava peels)

However, renewable energy sources like solar and wind are *intermittent*, they do not produce energy continuously. This creates a major challenge: *how to store energy for use when it is needed.*

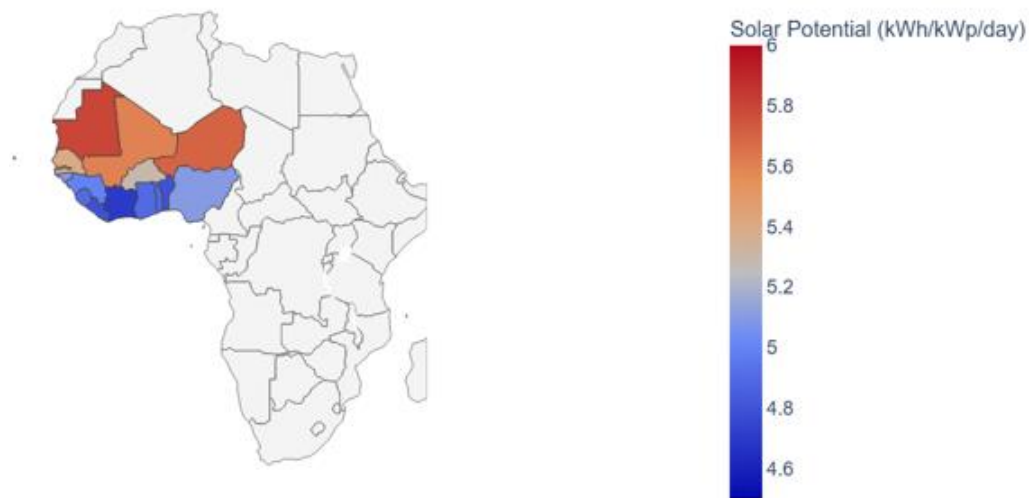


Figure 1.3 Solar Energy Potential of West Africa

1.4. Hydrogen Energy Solutions: A Strategic Opportunity

Hydrogen energy offers a powerful solution to many of West Africa's energy challenges. Hydrogen is not a primary energy source; it is an *energy carrier*. This means it can store energy and release it when needed. Using renewable electricity (such as solar), water can be split into hydrogen and oxygen through a process called **electrolysis**. The hydrogen produced, known as **green hydrogen**, can then be stored and used later.

1.4.1. How Hydrogen Solves Key Challenges?

- **Energy Storage:** Hydrogen stores excess solar energy generated during the day and provides power at night or during low production periods.
- **Reducing Diesel Dependence:** Hydrogen can replace diesel in generators and backup systems, lowering fuel costs and emissions.
- **Supporting Industry:** Hydrogen can be used in fertilizer production, refining, and heavy industries where electrification is difficult.
- **Clean Transport:** Hydrogen fuel cells can power buses, trucks, and other heavy vehicles with zero emissions.
- **Waste-to-Energy Opportunities:** Agricultural waste (e.g., cassava peels, rice husks) can be converted into **bio-hydrogen**, reducing open burning and pollution.

1.4.2. Why Hydrogen Fits West Africa?

- Abundant solar energy supports green hydrogen production
- Large agricultural sector provides biomass resources
- Growing energy demand creates a strong use case
- Opportunity to build local industries and technical skills

The hydrogen sector is creating new career opportunities, including:

- Electrolyser operation and maintenance
- Hydrogen storage and safety management
- Fuel cell installation and servicing
- Transport and distribution systems

Think It Through: Where in your community could hydrogen make the biggest impact, power supply, transport, or industry?

This chapter highlights a key message: West Africa's energy challenges are significant, but they also create opportunities for innovation and transformation. Hydrogen energy is a critical part of this transition. It complements renewable energy, improves reliability, and supports sustainable development. In the chapters that follow, you will learn the properties and types of hydrogen (green, blue, grey), hydrogen production methods, global hydrogen market trends and practical applications in power, transport, and industry.

Chapter Summary

West Africa faces major energy challenges, including unreliable electricity supply, dependence on diesel, and climate vulnerability. These issues limit economic growth and quality of life. The transition to clean energy is essential. While renewable energy sources are abundant, their intermittent nature requires effective storage solutions. Hydrogen energy provides a flexible and sustainable solution by storing renewable energy, reducing reliance on fossil fuels, supporting industrial and transport applications, and converting local waste into clean fuel.

Review Questions

1. What are two common effects of unreliable electricity in West African communities?
2. Why is reliance on diesel generators unsustainable?
3. What are the main drivers of energy transition in West Africa?
4. How does hydrogen help solve the problem of renewable energy intermittency?
5. Identify one potential hydrogen application in your local area and explain its benefits.

Chapter 2

Hydrogen Properties, Classifications and Application (H2-B1-2)

2.1. Hydrogen as an Energy Carrier

Hydrogen is considered one of the most promising clean energy carriers for future clean and sustainable energy systems. However, hydrogen is not a primary energy source like coal, oil, or sunlight. Instead, it must be produced from other resources such as water, natural gas, or biomass using different technologies.

An energy carrier is something that *stores energy and transports it from where it is produced to where it is used*. For example:

- Electricity carries energy through power lines.
- Batteries store electrical energy.
- Hydrogen stores energy in chemical form.

Today, the world mainly depends on fossil fuels such as oil, coal, and natural gas. These fuels are limited and also cause environmental problems such as *air pollution and climate change*. Because of these challenges, scientists and engineers are exploring cleaner energy solutions. Hydrogen is one of the important options being considered. Hydrogen can play a key role in *clean energy systems*, especially when it is produced using *renewable energy sources such as solar, wind, or hydropower*. When hydrogen is used in *fuel cells or burned as a fuel*, the main by-product is **water**. This makes hydrogen clean and environmentally friendly, as there is no carbon dioxide released.

2.2. Properties of Hydrogen

Hydrogen is the *lightest and most abundant element in the universe*. It has several unique physical and chemical properties that make it useful as an energy carrier. Its chemical symbol is H and written in molecular form as H₂. Its atomic number is 1. Hydrogen is 14 times lighter than air; thus, it diffuses rapidly in the atmosphere. Because of its low density, large storage volumes are required unless compressed or liquefied. The detailed physical and chemical properties are presented in the subsequent sections.

2.2.1. Physical Properties

Table 2.1. physical properties of H₂

Property	Value	Description
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Chemical symbol	H ₂	Diatomic molecule
Molecular weight	2.016 g/mol	Lightest molecule
Density (gas at STP)	0.0899 kg/m ³	Very low density
Boiling point	−252.9°C	Very low boiling temperature
Melting point	−259.2°C	Extremely cold for solid form
Color	Colorless	Invisible gas
Odor	Odorless	Cannot be detected by smell

2.2.2. Chemical Properties

Two hydrogen atoms combine to form one hydrogen molecule.



Important chemical characteristics include:

- Highly flammable with flammability range in air (4–75%)
- High combustion efficiency
- High ignition energy compared to gasoline vapor
- Produces water when burned

Hydrogen combustion reaction, which releases clean energy with no carbon emissions, is given as:

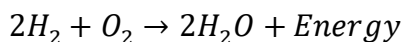


Illustration: Hydrogen is like a battery in gas form. It stores energy that was produced somewhere else,

2.2.3. Hydrogen Energy Density

Energy density describes the amount of energy stored per unit mass or per unit volume of a fuel. Two types of energy densities are important:

a. Gravimetric Energy Density

Energy per unit mass (MJ/kg). Hydrogen has very high gravimetric energy density compared to most fuels. As we can see from the Table 2.2, 1 kg of hydrogen contains nearly 3 times more energy than gasoline.

Table 2.2. Comparison of energy content different substances

Fuel	Energy Density (MJ/kg)
Gasoline	44
Diesel	45
Methane	55
Hydrogen	120

b. Volumetric Energy Density

Volumetric energy density is defined as energy per unit volume (MJ/L). Hydrogen has very low volumetric energy density because it is a light gas. Typical energy densities of hydrogen in its gas, liquid and solid forms are given in Table 2.3.

Table 2.3 Energy densities of hydrogen in its various forms

Fuel	Energy Density (MJ/L)
Hydrogen (gas)	~0.01
Liquid hydrogen	~8.5
Gasoline	~32
Diesel	~36

Because of this limitation, hydrogen must often be:

- Compressed (350–700 bar)
- Liquefied (-253°C)
- Stored in metal hydrides or chemical carriers

2.3. Classification of Hydrogen

We use special “colors” to show how clean or dirty hydrogen is. The color does not refer to the actual colour of the gas. Instead, it tells us how much pollution (especially carbon dioxide) is produced when making the hydrogen. Understanding these colors is very important for technicians and students in West Africa. It helps us choose the best and cleanest way to produce hydrogen using our local resources. Table 2.4 presents summary of color classification of the Hydrogen highlighting ways of production and environmental impacts.

- a) **Grey Hydrogen:** Grey hydrogen is the most common type used in the world today. It is made from natural gas using the Steam Methane Reforming (SMR) method. The carbon dioxide produced during the process is released into the air. It is the cheapest hydrogen available today. But it causes air pollution because of the carbon dioxide. Many industries in Nigeria currently use grey hydrogen because the country has natural gas.
- b) **Blue Hydrogen:** Blue hydrogen is also made from natural gas using SMR, but the carbon dioxide is captured and stored underground instead of being released into the air. It is cleaner than grey hydrogen. But its capturing the carbon dioxide makes the process more expensive.
- c) **Green Hydrogen:** Green hydrogen is the cleanest type. It is produced by electrolysis using electricity from solar panels or wind turbines. No fossil fuels are used. It produces almost zero pollution. When used, it only releases water. It is the best option for the future. However, it is still more expensive than grey hydrogen today, but prices are falling quickly.
- d) **Brown Hydrogen:** Brown hydrogen is made from coal at very high temperatures. It can be cheap in countries that have a lot of coal. But it produces a large amount of pollution and carbon dioxide and it is the dirtiest type of hydrogen and not good for the environment.

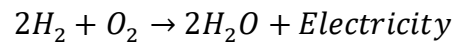
Table 2.4 Summary of color classification of the Hydrogen

Hydrogen Type	Production Method	Environmental Impact
Grey Hydrogen	Natural gas	High CO ₂ emissions
Blue Hydrogen	Natural gas + carbon capture	Lower emissions
Green Hydrogen	Water electrolysis using renewable energy	Very clean

2.4.Basic Principle of a Fuel Cell

A fuel cell converts hydrogen into electricity. It works like a battery but does not run out if fuel is supplied. Hydrogen enters the fuel cell from one side. Oxygen enters from the air on the other side. Inside the fuel cell, a chemical reaction occurs. Hydrogen splits into protons and electrons. Electrons flow through a circuit to produce electricity. Protons combine with oxygen to form water. This process produces electricity, heat, and water. There is no harmful emission.

Fuel Cell Reaction: Hydrogen + Oxygen → Electricity + Water



A simple concept block diagram illustrating hydrogen production using solar energy shown in Figure 2.1 below.

Hydrogen (H₂) → **Fuel Cell** → Electricity → Load (Light, Fan)
↓
Water (H₂O)

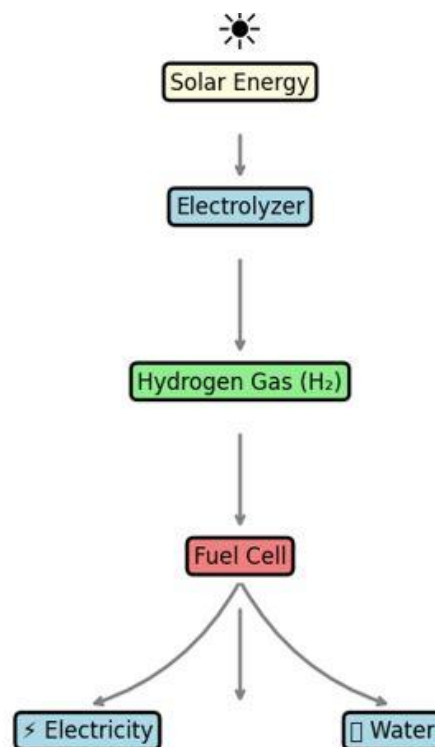


Figure 2.1 Solar energy to H₂ conceptual diagram

2.5. Renewable Integration of Hydrogen

Hydrogen is a great way to use clean renewable energy sources like the sun and wind. When solar panels or wind turbines generate electricity (especially when there's extra power available), this electricity can power a process called electrolysis. In electrolysis, water is split into hydrogen and oxygen using that electricity. The hydrogen produced can then be stored for later use. This creates solar-to-hydrogen or wind-to-hydrogen systems and allows renewables to be stored for a long time, helping to make clean energy more reliable even when the sun isn't shining or the wind isn't blowing.

The diagram in Figure 2.2 illustrates wind turbines and solar panels supplying electricity through converters to an electrolyzer unit that splits water into hydrogen (stored) and oxygen, with arrows showing the energy flow from renewables to hydrogen production and storage.

Thus, hydrogen can be produced from *renewable electricity* through water electrolysis, enabling:

- solar-to-hydrogen systems
- wind-to-hydrogen systems
- long-term renewable energy storage

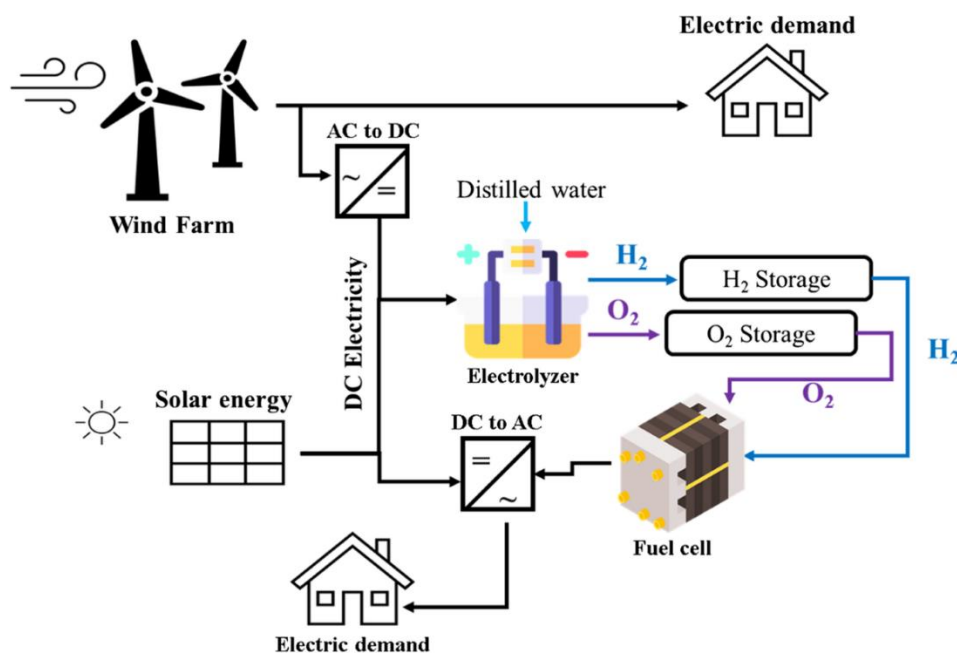


Figure 2.2 Renewable integration of H₂

2.6. Energy Storage Capability

Hydrogen can store surplus renewable energy and convert it back to electricity using fuel cells and gas turbines. This supports *grid stability and seasonal energy storage*. Hydrogen works like a battery for renewable energy, but one that can hold a lot of energy for a long time, even months or seasons. When there's extra solar or wind power (like during sunny days in Africa with high solar potential), it goes into electrolysis to make hydrogen from water. The hydrogen is stored safely in tanks. Later, when energy is needed (like at night or during low-wind periods), the hydrogen can be turned back into electricity using fuel cells (which combine hydrogen with oxygen to produce power cleanly) or gas turbines. This helps keep the electricity grid stable and provides energy when renewables aren't producing enough.

Illustration: Many African countries have high solar energy potential. This energy can be stored in hydrogen for later use.

For example: Solar power → Electrolysis → Hydrogen → Electricity at night.

This allows renewable energy storage for rural electrification.

The diagram in Figure 2.4 shows the sun shining on solar panels during the day, sending power to an electrolyzer that uses water to produce hydrogen stored in a tank, then hydrogen feeding back to produce electricity for use at night, like powering a home or light bulb.

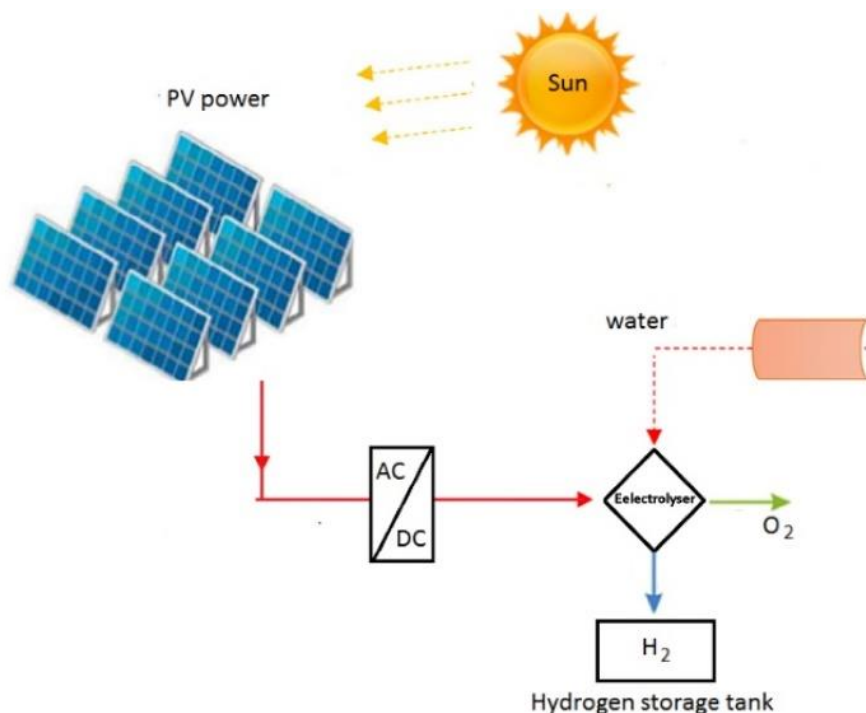


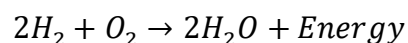
Figure 2.4 Solar Energy-to-Hydrogen Storage System

2.7. Advantages and Limitations of Hydrogen

Hydrogen offers several benefits but also has technological challenges.

2.7.1. Advantages of Hydrogen

a. Clean Energy Source: When used in fuel cells or combustion:



The only by-product is **water vapor**, making hydrogen environmentally friendly.

b. High Energy Content: Hydrogen has the *highest energy per unit mass of any fuel*. This makes it ideal for fuel cell vehicles, aerospace applications, and energy storage systems.

In the future, as the world gradually moves away from fossil fuels, *hydrogen and electricity are expected to become the two main energy carriers* used to supply energy for transportation, industries, homes, and other services. This change represents a transition from the fossil-fuel-based energy system to a new system often called the **hydrogen economy**.

2.7.2. Limitations of Hydrogen

- a) *Storage Challenges:* Due to low density, hydrogen storage requires high-pressure tanks, cryogenic systems and advanced materials.
- b) *Infrastructure Limitations:* Hydrogen requires new infrastructure such as pipelines, refueling stations and storage systems. Currently, hydrogen infrastructure is limited in many countries.
- c) *Production Cost:* Green hydrogen production using electrolysis is still *more expensive than fossil fuels*, although costs are rapidly decreasing.
- d) *Safety Concerns:* Hydrogen is highly flammable and difficult to detect (colorless and odorless). However, thanks to modern safety technologies, which made hydrogen systems reliable.

Thus, learners and technicians must understand hydrogen properties for safe storage and transport, leak detection and system maintenance.

Think It Through: Why is hydrogen considered an energy carrier rather than an energy source?

2.8.Applications of Hydrogen Energy Carrier

Hydrogen can be used in many sectors:

Transportation

- fuel cell electric vehicles
- hydrogen buses
- hydrogen trains

Power Generation

- fuel cell power plants
- hydrogen turbines

Industry

- steel production
- ammonia manufacturing
- petroleum refining

Energy Storage

- renewable energy storage
- power-to-gas systems

2.9.Chapter Summary

Hydrogen is an important clean energy carrier with significant potential in future energy systems. It has unique properties such as high energy density by mass, clean combustion, and compatibility with renewable energy systems. However, challenges such as storage, infrastructure, and cost still need to be addressed.

Hydrogen is classified into different types based on its production methods, including green, blue, and grey hydrogen. Among these, green hydrogen is the most sustainable option for achieving global carbon neutrality. Hydrogen's properties make it a powerful energy carrier. Different production methods determine its environmental impact, with green hydrogen being the most sustainable option.

Review Questions

3. What makes hydrogen an attractive energy carrier?
4. What makes hydrogen unique compared to other fuels?
5. Differentiate between green, blue, and grey hydrogen.
6. What is green hydrogen?
7. Why is green hydrogen preferred over grey hydrogen?
8. List two applications of hydrogen energy.
9. Which sectors can benefit from hydrogen technologies?
 - Case study: Hydrogen projects in Africa
 - Group discussion: Hydrogen vs batteries for energy storage

References

- [1] H201
- [2] current status
- [3]

Chapter 3

Global Hydrogen Economy and Market Trends

3.1. Introduction

Hydrogen is increasingly becoming an important part of the global shift toward clean and sustainable energy. Unlike fossil fuels, hydrogen burns without producing harmful emissions, making it a cleaner option for powering industries, transport, and electricity systems. It also plays a key role in storing energy generated from renewable sources such as solar and wind, which are abundant but not always available at all times. As a result, many countries around the world are investing in hydrogen technologies to meet their climate goals and improve energy security. This growing global interest is creating new economic opportunities, including the development of industries, infrastructure, and supply chains linked to hydrogen.

For regions like West Africa, this trend presents a valuable opportunity. With strong renewable energy potential and a growing need for reliable and affordable energy, hydrogen can support local development while also opening doors for exports. Importantly, the expansion of the hydrogen sector will create demand for skilled workers, making it highly relevant for TVET systems to prepare students for emerging jobs in this field.

3.2. Global Drivers of Hydrogen Growth

Several strong forces are driving the growing interest in hydrogen. Climate change policies are pushing governments to reduce pollution that negatively affects sectors like agriculture and fisheries, particularly in regions such as West Africa. At the same time, many countries have committed to net-zero emission targets by 2050, increasing the demand for cleaner energy solutions. Industries, including factories and refineries, are also seeking to decarbonize their operations in order to remain competitive in a low-carbon economy. In addition, concerns about energy security are encouraging nations to produce their own clean fuels, reducing reliance on expensive imported oil. These drivers matter to you because they create demand for skilled technicians right here in West Africa.

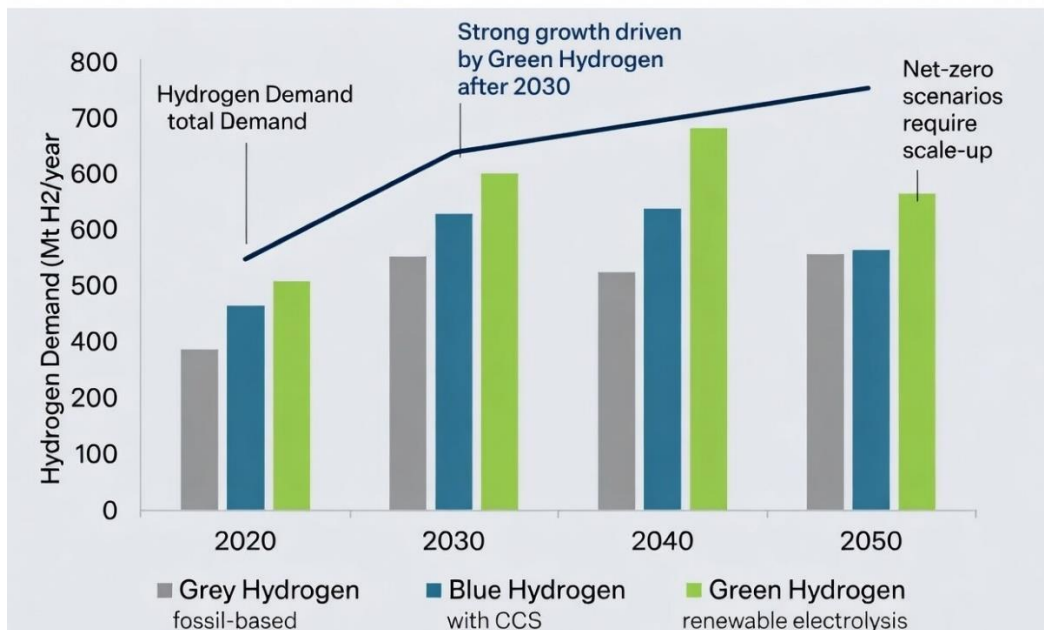


Figure 3.1 Global Hydrogen Demand Forecast

3.3. Key Hydrogen Markets

The global hydrogen economy is developing across several key regions, each with different roles and opportunities. Understanding these markets helps African countries and TVET trainees see where future jobs and partnerships may come from.

Europe is currently a leader in green hydrogen development. Many European countries are investing heavily in clean energy to meet strict climate targets. However, they do not have enough renewable energy to produce all the hydrogen they need, so they plan to import large amounts from other regions, including Africa. This creates opportunities for African countries to become exporters and for skilled workers to support production and export activities. **Asia**, especially countries like Japan and South Korea, also has strong demand for hydrogen. These countries have clear national strategies and are willing to pay for imported clean hydrogen because they have limited natural resources. They are investing in hydrogen technologies such as fuel cells, transport systems, and power generation, creating global demand for supply and technical expertise.

The **Middle East** is focusing on large-scale hydrogen projects mainly for export. Countries in this region use their abundant and low-cost solar energy to produce green hydrogen at competitive prices. They are developing advanced infrastructure and export systems, which makes them strong competitors but also potential partners for knowledge sharing. **Africa** is an

emerging and highly promising market. With vast solar and wind resources, Africa has the potential to produce green hydrogen at low cost. At the same time, local demand is growing for cleaner energy in industries, transport, and agriculture. This means Africa can play a dual role, both as a supplier to global markets and as a user of hydrogen to support its own development.

For TVET learners, these global markets highlight the importance of developing practical skills in renewable energy, plant operation, maintenance, and safety. As hydrogen projects expand across these regions, skilled technicians will be essential to support production, transport, and end-use systems both within Africa and in international projects.

3.4. Hydrogen Value Chain

The hydrogen value chain describes the full journey of hydrogen, from how it is made to how it is finally used as illustrated in figure 3.1. In Africa, this value chain is especially important because the continent has abundant solar and wind resources, which can be used to produce clean (green) hydrogen and support local development and jobs.

The first step is **production**, where hydrogen is made. In Africa, the most promising method is green hydrogen production using renewable energy such as solar in countries like Ethiopia, Namibia, and Morocco, or wind in coastal regions. This creates opportunities for technicians to install, operate, and maintain solar panels, wind turbines, and electrolysis systems. The second step is **storage**, which involves safely keeping hydrogen until it is needed. Hydrogen must be stored in special tanks or sometimes underground. This requires skilled workers who understand safety standards, pressure systems, and inspection procedures, important roles for TVET graduates trained in mechanical and safety skills.

The third step is **transport**, where hydrogen is moved from production sites (often in rural or coastal areas) to cities, industries, or export terminals. In Africa, this may involve trucks, pipelines, or ships. Logistics technicians and transport operators are needed to handle equipment, monitor safety, and manage supply chains. The final step is **end-use**, where hydrogen is applied in real sectors. In Africa, this includes using hydrogen in factories, powering buses or trucks in cities, generating electricity, or producing fertilizers for agriculture. For example, local fertilizer production using hydrogen can reduce dependence on imports and support farmers. This stage creates jobs for plant operators, maintenance technicians, and process controllers.

Each part of the hydrogen value chain requires trained workers with practical skills. For instance, a logistics technician must ensure that hydrogen tanks are properly sealed and safe

before transport, while an electrical technician may maintain the renewable energy systems used in production. This makes hydrogen not only an energy solution but also a strong opportunity for skills development and employment across Africa.

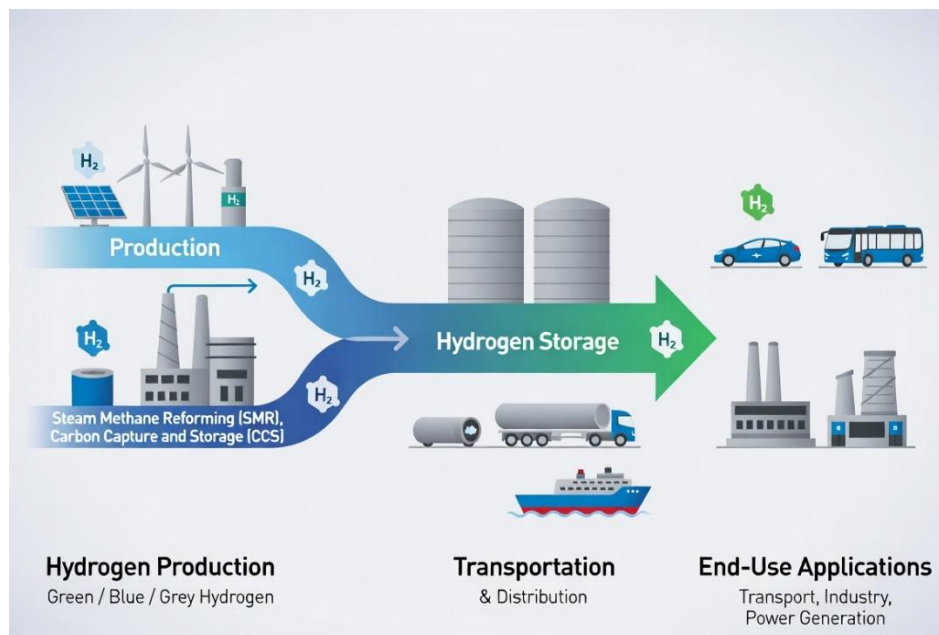


Figure 3.1 Hydrogen Value Chain in Africa

3.5. Africa's Position in the Hydrogen Economy

Africa is in a strong position to become an important player in the global hydrogen economy. This is mainly because the continent has abundant natural resources, especially sunshine and wind, which are key for producing green hydrogen. Figure 3.2 illustrates Africa's Hydrogen Opportunity Zones. Countries such as Namibia, Morocco, Kenya, and Ethiopia can generate large amounts of renewable energy at relatively low cost. This creates an opportunity not only to meet local energy needs but also to export green hydrogen and related products, such as ammonia, to regions like Europe and Asia where clean energy demand is growing.

At the same time, hydrogen can be used locally to address some of Africa's major challenges. For example, in rural areas where electricity access is limited, green hydrogen can support mini-grids and backup power systems. In industries such as food processing, mining, and transport, hydrogen offers a cleaner alternative to diesel and other fossil fuels. This can help reduce pollution, lower fuel costs over time, and improve productivity.

Regional cooperation is also starting to grow. In West Africa, ECOWAS countries are discussing joint strategies to develop hydrogen projects, share knowledge, and build technical

capacity. These collaborations can help countries learn from each other, reduce costs, and create regional markets for hydrogen technologies.

For TVET systems, this presents a major opportunity. As hydrogen projects expand, there will be increasing demand for skilled workers such as renewable energy technicians, plant operators, safety inspectors, welders, and logistics personnel. Trainers should therefore prepare students with practical skills related to renewable energy systems, basic chemistry of hydrogen, safety procedures, and equipment maintenance. In this way, Africa's position in the hydrogen economy is not only about energy, but also about job creation, skills development, and sustainable economic growth.

Industry Insight:

New roles are opening for TVET graduates:

- Hydrogen plant operators
- Logistics technicians
- Safety inspectors

These jobs pay well and need practical skills you can learn in your workshop.

Real-Life Examples

1. In rural northern Ghana, a small solar-powered pilot project produces green hydrogen that powers generators for a local maize mill. This gives the mill steady electricity even at night and creates two new technician jobs for young people who trained in basic electrical and safety skills.
2. In Senegal, ECOWAS-supported talks have started small hydrogen plans linked to agriculture. Farmers near Dakar hope to use clean hydrogen to make fertilizer locally instead of importing expensive chemical versions. This cuts costs for small farms and opens work for safety inspectors and plant operators.
3. In Ethiopia, a major international investment led by China's Ming Yang company plans to spend over \$10 billion on renewable energy, green hydrogen, and ammonia production projects. These large-scale developments aim to use Ethiopia's strong renewable energy resources to produce clean fuels for both local use and export, potentially creating jobs in construction, plant operation, and engineering while supporting the country's industrial growth.

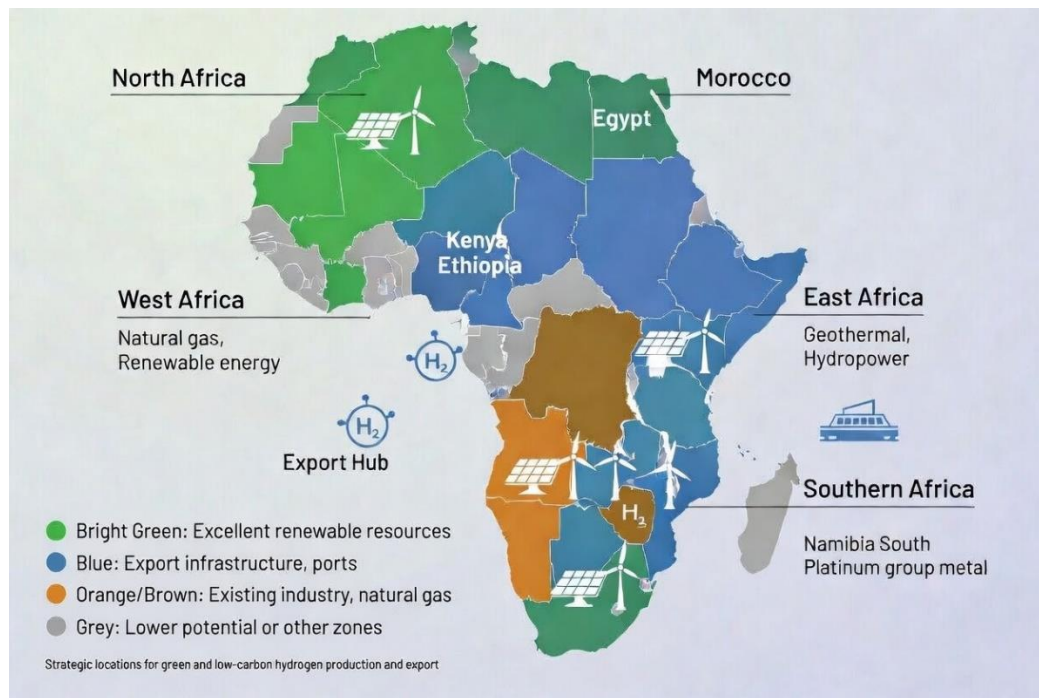


Figure 3.2 Hydrogen Opportunity Zones in Africa

3.6. Chapter Summary

Hydrogen is becoming a key part of the global energy transition because it is a clean fuel that helps reduce pollution. Many countries are investing heavily in hydrogen due to important drivers such as climate change policies, net-zero targets, industrial decarbonization, and the need for better energy security. The main hydrogen markets today are Europe, which leads in green hydrogen, Asia (especially Japan and South Korea), the Middle East with its export-focused projects, and Africa, which is an emerging player with great potential.

The hydrogen value chain includes four important stages: production (especially green hydrogen made from solar or wind), storage, transport, and end-use in industries, transport, and power generation. Africa has strong advantages because of its abundant sunshine and wind resources. It can export green hydrogen to other regions while also using it locally to improve electricity access in villages, support agriculture, and help small industries. ECOWAS is already supporting regional cooperation in this area.

New job opportunities are opening for TVET graduates, including hydrogen plant operators, logistics technicians, and safety inspectors. Overall, the global hydrogen economy is growing rapidly, and West Africa is well positioned to benefit if students develop the practical skills needed for these new roles. The chapter encourages thinking about whether Africa should focus more on exporting hydrogen or using it to solve local energy problems.

Review Questions

1. Name two global drivers of hydrogen growth.
2. What are the four parts of the hydrogen value chain? (short answer)
3. True or False: Africa only has potential for exporting hydrogen and cannot use it locally.
4. Which region is known for green hydrogen leadership? (a) Europe (b) Middle East (c) Africa
5. Name one new job that a TVET graduate could do in the hydrogen sector.

Activity for Students

Group Discussion – (30–40 minutes)

Work in groups of 4–5. Use the Think It Through question: Should Africa focus more on exporting hydrogen or using it locally?

- List two reasons for exporting and two reasons for local use.
- Give one example from your own town or region (a farm, market, or workshop).
- Draw a simple value chain on paper showing where hydrogen could start in your community (use solar panels or wind as the start point).

Materials needed: paper, pen or chalkboard. Share your group's top idea with the class.

Chapter 4

Overview of Hydrogen Production Pathways (H2-B1-4)

4.1. Introduction

Hydrogen can be produced through different methods depending on available natural resources, technology, and cost. Unlike fossil fuels that are taken directly from the ground, hydrogen must be produced from substances such as water, natural gas, or biomass. These production methods are called hydrogen production pathways. Different regions of the world use different methods based on what resources are available.

For example:

- Countries with strong sunlight can use solar energy for hydrogen production.
- Countries with natural gas resources often use reforming methods.
- Agricultural regions can use biomass waste.

Understanding these methods helps technicians and learners choose the most suitable and sustainable way to produce hydrogen, especially in African countries where renewable resources are abundant.

4.2. Main Production Methods

There are several important methods used to produce hydrogen. Each method has its own advantages, disadvantages, and environmental impacts.

4.2.1. Electrolysis (Green Hydrogen)

Electrolysis is the process of splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) using electricity. When the electricity comes from renewable energy such as solar or wind, the hydrogen produced is called green hydrogen. The production of green hydrogen from solar energy is illustrated in figure 4.1. Electrolysis is one of the most important hydrogen production methods for clean energy systems. It uses water (H_2O), electricity (preferably renewable) and electrolyser equipment as shown in figure 4.1. Inside the electrolyser, water is split into hydrogen and oxygen using electric current.

Electrolysis system components include:

- Power source (solar panels or grid),
- Electrolyser unit,

- Water supply system and
- Gas storage tanks

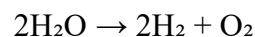
Illustration: Electrolysis works like charging a battery, but instead of storing electricity, it stores energy in hydrogen gas.

Electrolysis is ideal for solar-powered systems in West Africa because:

- Sunlight is available throughout the year,
- It reduces dependence on imported fuels, and
- It supports clean and sustainable energy systems

In electrolysis process diagram (Figure 4.1), water enters the electrolyser, electricity splits it into hydrogen and oxygen, hydrogen gas is collected and is stored in tanks while oxygen is released or used for other purposes.

Process reaction: Water + Electricity $\rightarrow$ Hydrogen + Oxygen



Advantages:

- Produces clean hydrogen with no carbon emissions,
- Uses renewable energy,
- Suitable for rural and off-grid areas

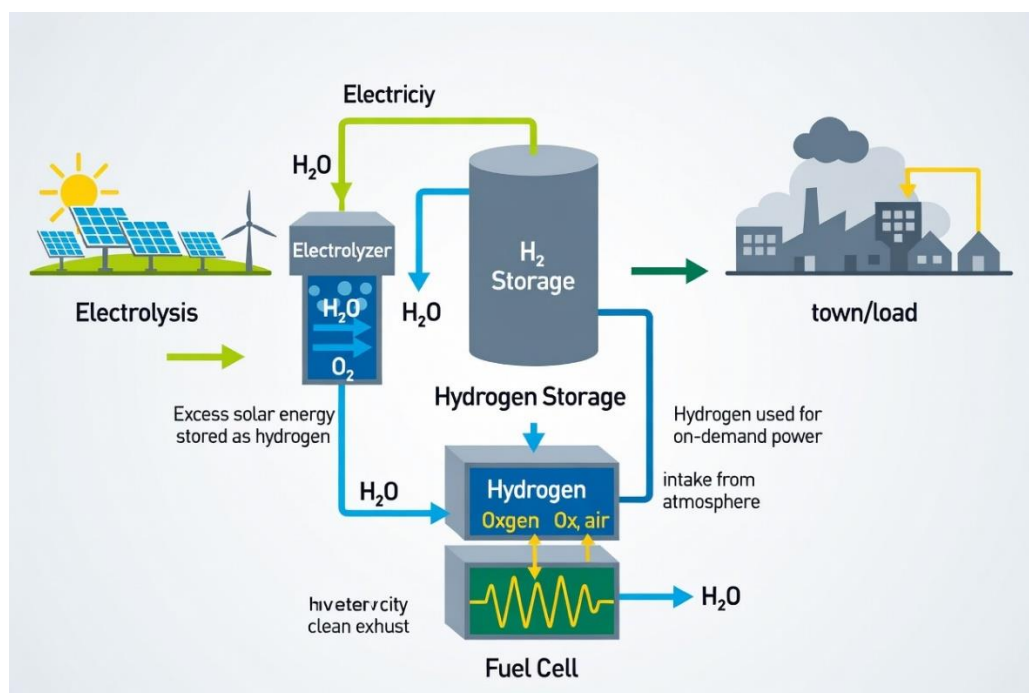


Figure 4.1 Green Hydrogen production from solar energy using electrolysis process

Figure 4.1 shows solar-to-hydrogen system layout:

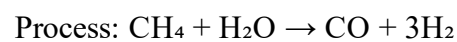
Solar panels → electrolyser → hydrogen storage → energy use.

This can be adopted locally in West Africa.

4.2.2. Steam Methane Reforming (SMR)

Steam Methane Reforming is the most widely used method today. It uses natural gas (methane) and steam to produce hydrogen. Figure 4.2 illustrates SMR Process Flow:

Natural gas + steam → reactor → hydrogen + CO₂.



Advantages:

- Mature and widely used technology,
- Lower cost compared to electrolysis

Disadvantages:

- Produces carbon dioxide (CO₂),
- Contributes to climate change if emissions are not captured

Illustration: SMR is like cooking gas with steam to extract hydrogen, but it releases smoke (CO₂).

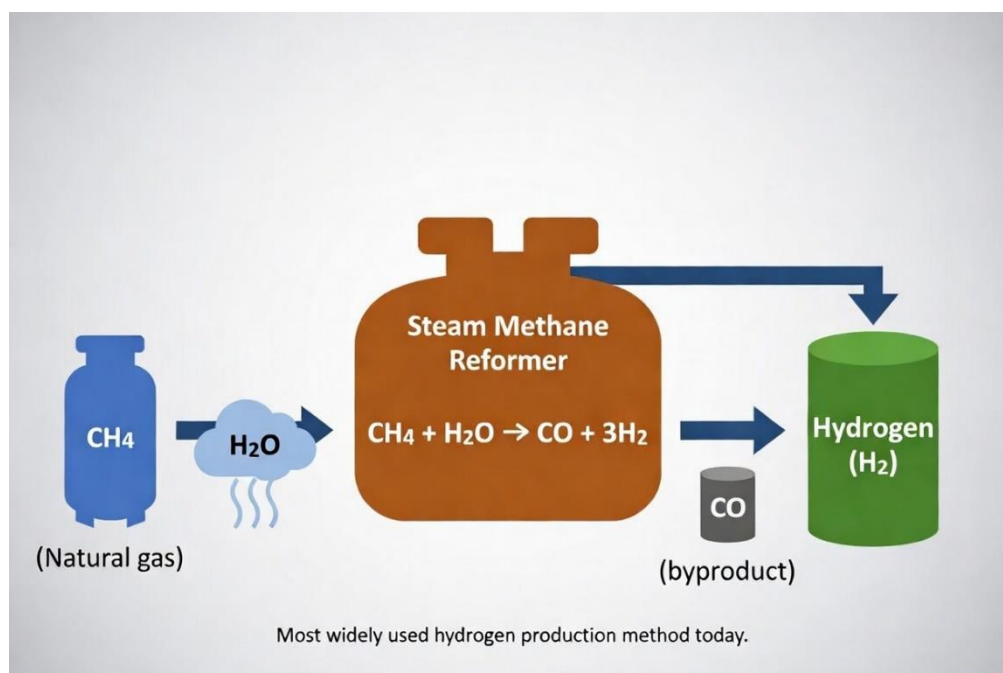


Figure 4.2 Hydrogen production from Steam Methane Reform method

4.2.3. Biomass Gasification

Biomass gasification uses organic materials such as agricultural waste to produce hydrogen. Materials like cassava peels, rice husks, and wood residues can be used. Figure 4.3 Biomass to Hydrogen Pathway: Agricultural waste → gasifier → hydrogen production.

Process: Biomass + Heat → Gas mixture → Hydrogen

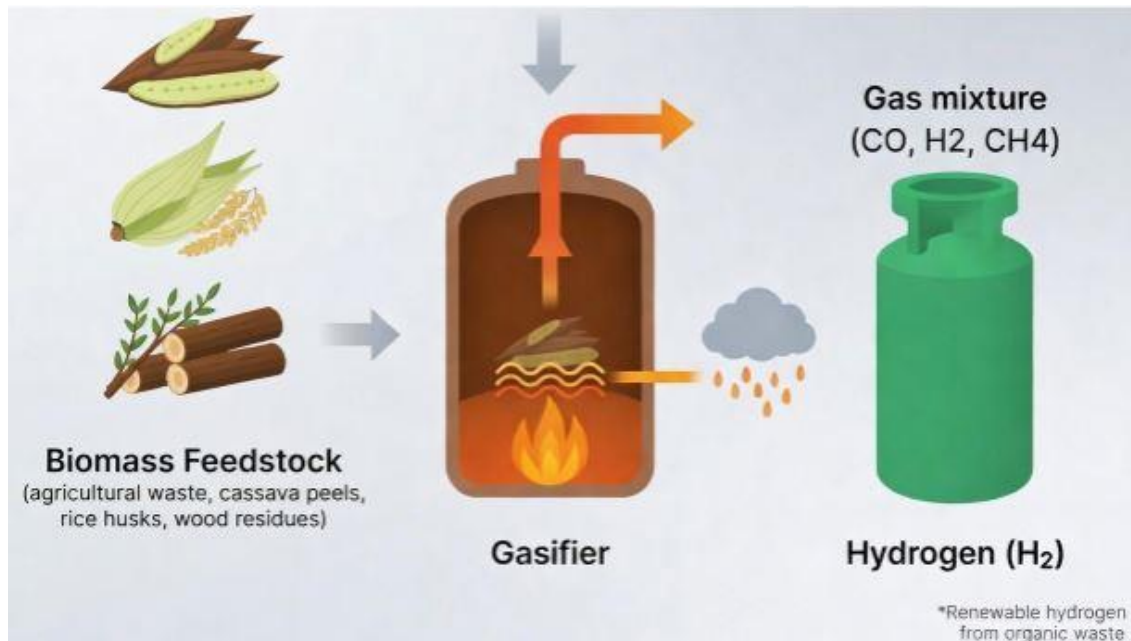


Figure 4.3 Hydrogen production from Steam Methane Reform method

Advantages:

- Uses local agricultural waste
- Reduces environmental pollution
- Creates job opportunities in rural areas

4.3.4. Methane Pyrolysis

Methane pyrolysis splits methane into hydrogen (Turquoise color hydrogen) and solid carbon instead of carbon dioxide.

Process: $\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2$

Advantages:

- Produces hydrogen without CO₂ emissions
- Solid carbon can be used in industries

Disadvantages:

- Technology is still developing
- Requires high temperature systems

4.4. Local Production Opportunities

Hydrogen production can be adapted to local conditions in West Africa and Sub-Saharan regions.

4.4.1. Solar-Powered Electrolysis

Many African countries have strong sunlight. Solar panels can generate electricity to power electrolysis systems as illustrated in Figure 4.1, in which energy transition will be:

Solar energy → Electrolysis → Hydrogen → Electricity or fuel

Benefits:

- Clean energy production,
- Suitable for rural electrification,
- Reduces diesel generator use

4.4.2. Agricultural Waste to Hydrogen

Agricultural residues such as cassava peels, rice husks and maize stalks can be converted into hydrogen using biomass gasification.

Benefits:

- Waste management,
- Job creation,
- Local energy production

4.4.3. Small-Scale Decentralized Systems

Small hydrogen production units can be installed in villages, farms, or small industries.

Advantages:

- Independent energy systems,
- Reduced energy transport cost and
- Easy maintenance by local technicians

Industry Insight:

Technicians in hydrogen production systems perform important roles such as:

- Installing and maintaining electrolyser systems,

- Ensuring water purification before electrolysis,
- Monitoring system efficiency and performance,
- Checking for leaks and ensuring safety,
- Managing hydrogen storage systems

These skills are important for future jobs in clean energy industries.

Think It Through: What local resource (solar, water, biomass) could be used for hydrogen production in your area? How can this resource help improve energy supply in your community?

Chapter Summary

Hydrogen can be produced through different pathways such as electrolysis, steam methane reforming, biomass gasification, and methane pyrolysis. Each method depends on available resources and technology. Electrolysis is the cleanest method when powered by renewable energy, producing green hydrogen with no carbon emissions. For African countries, especially those with strong sunlight and agricultural resources, green hydrogen production offers a sustainable and practical solution. Local production systems can create jobs, improve energy access, and support environmental protection.

Review Questions

1. What is electrolysis?
2. List two main hydrogen production methods.
3. Compare electrolysis and steam methane reforming.
4. How can agricultural waste be used to produce hydrogen?
5. What are the benefits of small-scale hydrogen systems?

Chapter 5

Overview of Hydrogen Applications (H2-B1-5)

5.1. Introduction

Hydrogen is a flexible energy carrier that can be used in many sectors of the economy. It can provide electricity, power vehicles, and support industrial processes. Because of its clean nature and ability to store energy, hydrogen plays an important role in the transition to sustainable energy systems. Unlike fossil fuels, hydrogen can be used without producing harmful emissions when applied in fuel cells. This makes it suitable for countries aiming to reduce pollution and improve energy access. In West Africa, hydrogen can support development in rural and urban areas by providing reliable and clean energy solutions.

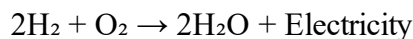
5.2. Power Generation

Hydrogen can be used to generate electricity in a clean and efficient way. One of the main technologies used is the fuel cell.

a) Fuel Cells Generate Electricity

A fuel cell converts hydrogen into electricity through a chemical reaction with oxygen, as illustrated in Figure 5.1.

Process: Hydrogen + Oxygen → Electricity + Water



Advantages:

- Clean energy (only water is produced)
- Quiet operation
- High efficiency

Illustration: A fuel cell works like a battery that keeps producing electricity as long as hydrogen is supplied.

b) Backup Systems for Mini-Grids

Hydrogen can be used as a backup energy source for mini-grids in rural areas. When solar or wind energy is not available, stored hydrogen can be used to generate electricity.

Example:

Daytime: Solar power → Hydrogen production

Nighttime: Hydrogen → Electricity

Benefits:

- Reliable power supply

- Supports rural electrification
- Reduces power interruptions

c) Replacement for Diesel Generators

Many communities and businesses in Africa use diesel generators. These generators are expensive and pollute the environment. Hydrogen fuel cells can replace diesel generators.

Advantages:

- No air pollution
- Lower noise
- Reduced fuel cost over time

Figure 5.1 illustrates hydrogen fuel cell power system depicting a process: Hydrogen enters fuel cell → electricity produced → water released.

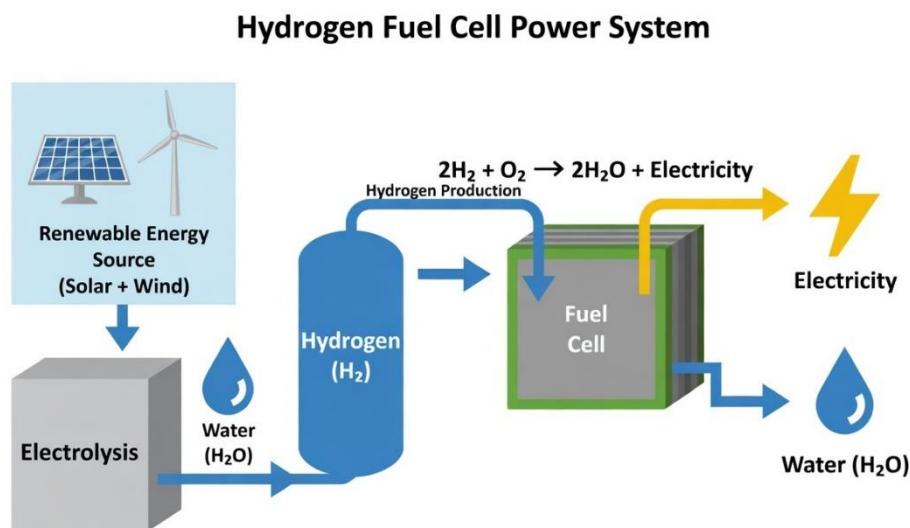


Figure 5.1. Hydrogen Application for Power Generation

5.3. Transport Applications

Hydrogen is increasingly used in transportation as a clean fuel alternative.

a) Hydrogen Buses and Trucks

Hydrogen-powered buses and trucks use fuel cells to generate electricity for driving. These vehicles are suitable for long distances and heavy loads.

Advantages:

- Fast refueling

- Long driving range
- Reduced emissions

b) Fuel Cell Electric Vehicles (FCEVs)

Fuel Cell Electric Vehicles use hydrogen instead of batteries to produce electricity.

Examples:

- Hydrogen cars
- Delivery vehicles
- Utility vehicles

Benefits:

- Zero emissions
- Efficient performance
- Suitable for urban and intercity travel

c) Clean Public Transport

Hydrogen can improve public transport systems by reducing pollution in cities. For example: Hydrogen buses in cities reduce smoke and improve air quality. In African cities with growing populations, hydrogen transport can:

- Reduce traffic pollution
- Improve public health
- Create modern transport systems

Figure 5.2 illustrates the Hydrogen Transport System:

Hydrogen tank → fuel cell → motor → vehicle movement

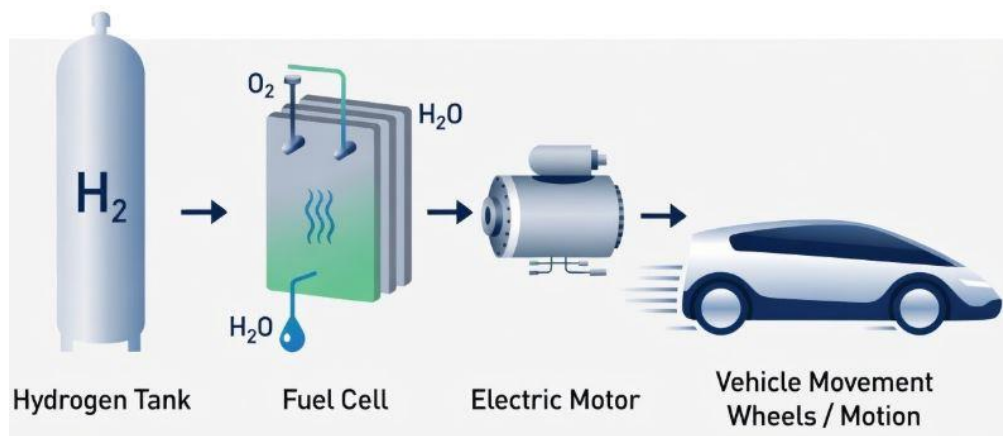


Figure 5.1 Hydrogen Transport System for FCEV Power Train

5.4. Industrial Applications

Hydrogen is widely used in industries both as a raw material and as a clean energy source. One of its main uses is in **fertilizer production**, where hydrogen is combined with nitrogen from the air to produce ammonia (NH_3). Ammonia is essential for making fertilizers that improve soil fertility and increase crop yields. This directly supports agriculture, which is a key sector in many African countries.

Hydrogen is also used in **steel production** as a cleaner alternative to coal. Traditional steel-making processes release large amounts of carbon dioxide, but using hydrogen can significantly reduce these emissions. This leads to a cleaner production process and supports efforts to reduce environmental pollution.

In addition, hydrogen plays an important role in **oil refining**. It is used to remove impurities such as sulfur from fuels like diesel and petrol. This improves fuel quality and reduces harmful emissions. For TVET learners, these industrial applications highlight opportunities in plant operation, maintenance, and safety management in modern industries.

5.5. Local Use Cases in West Africa

Hydrogen can also be applied in practical ways to meet local needs across Africa, especially in areas where energy access and economic development are priorities.

- ***H2 in rural electrification:*** In *rural electrification*, hydrogen can help provide electricity to off-grid communities. For example, solar energy can be used to produce hydrogen through electrolysis during the day. The hydrogen is then stored and later converted back into electricity when needed, such as at night. This improves access to reliable power, supporting homes, schools, and health services.
- ***H2 in agro-processing:*** Hydrogen is also useful in *agro-processing*, where it can power machines used for activities such as grinding grains, drying crops, and processing cassava. This increases productivity, reduces post-harvest losses, and creates job opportunities in rural areas.
- ***H2 in clean transport systems:*** Another important application is in *clean transport systems*. Hydrogen-powered buses and delivery vehicles can replace diesel-powered ones in cities and towns. This reduces air pollution, lowers fuel costs over time, and promotes more sustainable urban transport.

Benefits:

- Reduced pollution
- Lower fuel costs
- Sustainable urban transport

Figure 5.2 illustrates local hydrogen application system with a process: Solar → Hydrogen → Electricity, transport, and agro-processing.

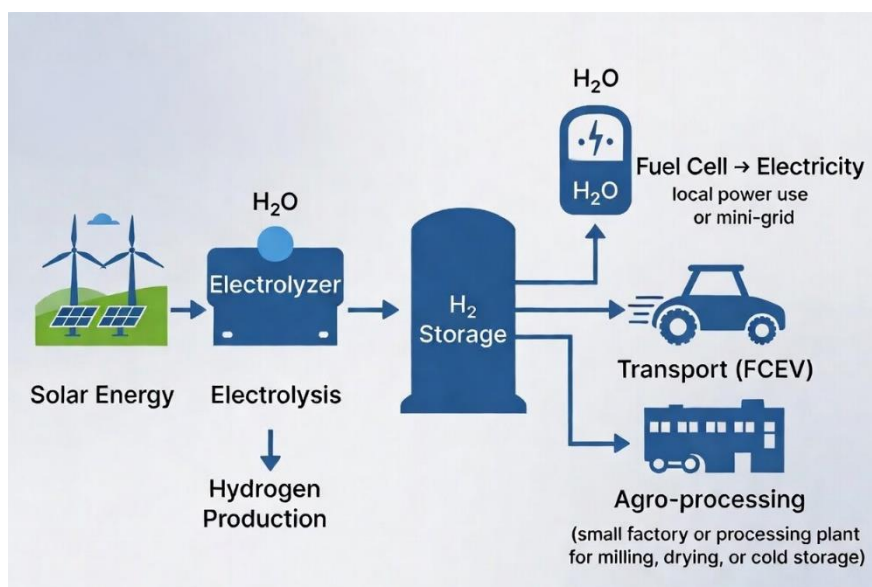


Figure 5.2 Local Hydrogen Application System

Industry Insight: Technicians are needed in hydrogen applications for the following roles:

- Fuel cell installation and maintenance
- System integration (connecting hydrogen systems with power or transport systems)
- Safety operations (handling hydrogen safely and preventing leaks)
- Monitoring system performance and efficiency

These roles are important for building a skilled workforce in the hydrogen economy.

Think It Through: Which hydrogen application would have the biggest impact in your country? Would it be power generation, transport, or industrial use? Why?

Chapter Summary

Hydrogen has many applications across power generation, transport, and industry. It can be used to produce clean electricity using fuel cells, power vehicles such as buses and cars, and support industries like fertilizer production and steel manufacturing. In West Africa, hydrogen

can improve rural electrification, support agro-processing, and provide clean transport solutions. Because of its flexibility and environmental benefits, hydrogen is an important energy solution for the future.

Review Questions

1. How do fuel cells generate electricity?
2. Name two transport uses of hydrogen.
3. Why is hydrogen useful in industry?
4. Give one example of hydrogen use in power generation.
5. How can hydrogen support rural electrification?
6. What roles do technicians play in hydrogen applications?

H2-B2: Hydrogen Safety and Risk Awareness

LEARNING OBJECTIVES

By the end of this chapter, learners will be able to:

- Identify hydrogen hazards and risks
- Explain safety standards and safe handling principles
- Recognize emergency response procedures
- List three locally available tools for hydrogen leak detection in West African workshops

CHAPTER 1

H2-B2-1 – Physical and Chemical Safety Properties

1.1.Introduction

Hydrogen is very different from common fuels like **diesel** and **LPG (cooking gas)**, and because it behaves differently, the old ways of working can become dangerous if they are not changed. In many **West African countries** such as **Nigeria**, **Ghana**, and **Senegal**, technicians are already familiar with diesel generators, LPG cylinders, and fuel storage systems. These fuels have strong smells, visible flames, and more predictable behavior. For example, diesel spills can be seen on the ground, LPG leaks can often be detected by smell, and their flames are easy to see. Hydrogen, however, does not behave this way. It has no smell, no color, and burns with a flame that is very difficult to see, especially in daylight. It also moves very quickly and rises upward. This means a leak can occur without being noticed, and a fire may be present without being clearly visible.

Because of this, many common habits used by technicians can become unsafe. For instance, checking for gas leaks by smelling, looking for visible flames, or focusing only on the ground level are methods that may work for LPG or diesel but are not reliable for hydrogen. A technician in **Ghana**, for example, might inspect only the floor area for a leak, while hydrogen gas has already risen and collected near the roof, creating a hidden danger. For this reason, working with hydrogen requires a new way of thinking. Technicians must begin to think upwards instead of downwards, rely on proper tools instead of their sense of smell, and always assume that a leak could be present even if it is not obvious. Safety depends on understanding how hydrogen behaves, following correct procedures, and avoiding assumptions based on experience with other fuels. Understanding the physical and chemical properties of hydrogen

is therefore the first and most important step to staying safe. When technicians understand these properties well, they can prevent accidents, protect lives and equipment, and work confidently with modern energy systems. Hydrogen can be used safely, but only when it is properly understood and handled with care.

1.2.Key Safety Properties of Hydrogen

Hydrogen has five important properties that every technician must know:

- *Very Light Gas*: Hydrogen is the lightest gas in the world. When it leaks, it does not stay on the ground. It rises very quickly to the ceiling or roof.
- *Colorless and Odorless*: Hydrogen has no colour and no smell at all. This means you cannot see it and you cannot smell it if there is a leak.
- *Highly Flammable*: Hydrogen catches fire very easily. Even a tiny spark can start a fire. In West African workshops, sparks often come from faulty wiring, generator switches, or phone chargers.
- *Nearly Invisible Flame*: When hydrogen burns, the flame is pale blue. In bright daylight, the flame is almost invisible. You may have fire in front of you but still not see it clearly.
- *Wide Flammability Range*: Hydrogen can burn even when there is only a small amount mixed with air. This makes it easier for a dangerous mixture to form.

1.3. Why These Properties Matter in West Africa?

Most workshops in West Africa are hot, poorly ventilated, and sometimes crowded. These conditions make hydrogen more dangerous. Example – Workshop in Northern Nigeria: The sun makes the workshop very hot. Hot air rises, and hydrogen rises even faster. If there is no good ventilation at the roof, hydrogen gas can collect near the ceiling. One small spark can then cause a big fire or explosion. Another example – Small Garage in Senegal: A technician may check only the floor for leaks because that is what he does with LPG. But hydrogen leak will be above his head near the roof. He may miss the danger completely.

1.4.Key Safety Rules

- Always check high places first – roof, ceiling, and top of pipes
- Install roof vents or fans to let hydrogen escape
- Never depend on your nose or eyes to find a leak
- Keep all spark sources away from hydrogen equipment
- If you are not sure, always assume there may be a leak

Figure 1.1: How Hydrogen and LPG Behave Differently

Table 1.1. Comparison between H₂ and LPG properties

Property	Hydrogen	LPG
Weight	Very light	Heavy
Where it goes	Rises to the roof	Stays near the floor
Smell	No smell	Strong smell
Flame	Almost invisible	Bright and easy to see
Leak detection	Very difficult	Easier

1.5.Common Mistakes to Avoid

- Checking only the floor for leaks
- Trying to smell the gas
- Ignoring roof ventilation
- Thinking “no smell means no problem”
- Safety Warning:

 Do NOT ignite hydrogen indoors. Always do this demonstration outdoors with proper supervision.

Brainstorming Questions (Class Discussion)

1. Why is hydrogen more dangerous to detect than LPG in a busy West African workshop?
2. How would poor roof ventilation affect hydrogen safety in a hot Senegalese workshop?
3. Can you rely on smell to detect hydrogen leaks? Why not?

1.6.Chapter Summary

Hydrogen is a very light gas that is invisible and has no smell, making it difficult to detect without proper tools. It rises quickly when released and tends to collect near the roof rather than staying close to the ground. Hydrogen also catches fire very easily and burns with a flame that is almost invisible, especially in daylight, which increases the risk of unnoticed fires. For this reason, technicians must always check high points such as ceilings and elevated pipe sections when inspecting for leaks, not just the ground level. Good roof ventilation is therefore one of the most important safety measures, as it helps remove any leaked hydrogen before it can build up and create a dangerous situation.

Chapter 2

H2-B2-2: Fire, Explosion, and Leakage Risks

2.1. Introduction

Hydrogen is very useful, but it can cause fire or explosion if we do not handle it carefully. The biggest problem is that hydrogen leaks are invisible and spread very fast. In many West African workshops, people are used to diesel and LPG. With hydrogen, small mistakes can quickly become dangerous. That is why every technician must understand the fire and explosion risks clearly.

2.2. Main Risks of Hydrogen

When working with hydrogen, there are *three major risks* you must always remember. These risks are different from what you are used to with diesel or LPG, so you must pay close attention.

a) *Small leaks spread quickly:* Hydrogen can escape through *very small openings*, even tiny holes or loose fittings. Because hydrogen is *very light*, it moves *very fast* and spreads quickly into the air.

This means:

- A small leak can become a *big problem in a short time*
- The gas can spread across the workshop before you notice

For example, in a small workshop in *Nigeria*, a loose pipe connection may not look serious. But within minutes, hydrogen can fill the upper part of the room.

Safety tip: Always tighten fittings properly and check connections regularly.

b) *Ignition sources are everywhere:* Hydrogen catches fire very easily.

Even a *small spark or heat source* can start a fire. In many *West African workshops*, ignition sources are common, such as:

- Faulty electrical wiring
- Light switches
- Diesel generators
- Phone chargers
- Metal tools hitting each other

This means you may not see danger, but a spark can ignite hydrogen instantly

For example, in *Ghana*, switching on a light in a poorly ventilated room with a leak can cause a fire.

Safety tip: Keep all electrical systems in good condition and avoid sparks near hydrogen systems.

c) *Invisible Flame Makes Fire Hard to Detect:* Hydrogen burns with a *pale blue flame* that is *very difficult to see*, especially during the day.

This means:

- A fire can be burning, but you *may not notice it*
- You may walk into a flame without knowing

Unlike LPG, whose flames are *bright and visible*, Hydrogen flames are *almost invisible*. For example, in a certain workshop, a technician may not see a hydrogen flame but may feel heat suddenly.

Safety tip: Always be alert. If you suspect a leak, do not assume the area is safe.

Key safety reminder

- A small leak can spread fast,
 - Sparks are common in workshops
 - Fires may be invisible
- ✓ *Always act early, even if you are not sure. Safety first.*

2.3. Common Ignition Sources in West Africa

In many *West African workshops*, there are everyday items that can produce sparks or heat. These items may seem normal, but when hydrogen is present, they become very dangerous ignition sources. For example, *faulty electrical wiring*, which is common in some *Ghanaian* workshops, can create sparks due to exposed wires, loose connections, or overloaded sockets. Similarly, *diesel generators*, widely used in places like *Benin*, can produce sparks during startup or generate high heat from engine parts. Even *mobile phone charging points* can overheat and create small sparks, while *electric switches and old extension boxes* may produce sparks when turned on or off. These are everyday tools, but when hydrogen is present, they can easily start a fire.

👉 Common ignition sources include:

- Faulty or exposed electrical wiring
- Sparks from diesel generators
- Overheating phone chargers
- Old switches and damaged extension boxes

👉 **Key message:** Always remember that normal workshop items can become dangerous when hydrogen is in use. Stay alert at all times.

2.4. Important Safety Rules (Must Follow Every Day)

To stay safe when working with hydrogen, technicians must follow strict safety rules every day. These rules are simple but very important for preventing accidents. First, never use an open flame such as a lighter, match, or candle to test for leaks, because hydrogen can ignite instantly. Electrical systems must always be kept in good condition, meaning faulty wires should be repaired immediately, damaged sockets replaced, and extension boxes not overloaded. Where possible, technicians should use *spark-proof tools* to reduce the chance of accidental sparks. It is also important to place clear safety signs in visible areas so that everyone is aware of the danger. Finally, hydrogen work areas must always be treated as *high-risk zones*, where extra care and attention are required at all times.

👉 Important safety rules:

- Never use open flames to check for leaks
- Keep electrical systems in good condition
- Repair faulty wiring immediately
- Use spark-proof tools whenever possible
- Display clear safety signs (“No Smoking”, “No Naked Flame”)
- Always treat hydrogen areas as high-risk zones

👉 **Key message:** Safety depends on daily discipline. Following these rules can prevent fires, explosions, and injuries.

Table 2.1. Real risk comparison:

Fuel	Leak Type	Behavior	Fire Spread
Diesel	Visible spill	Heavy fumes, stays low	Slow
Hydrogen	Invisible leak	Odorless, rises very fast	Very rapid

It is important to understand how hydrogen is different from diesel. Hydrogen fires spread much faster than diesel fires, so quick action is very important.

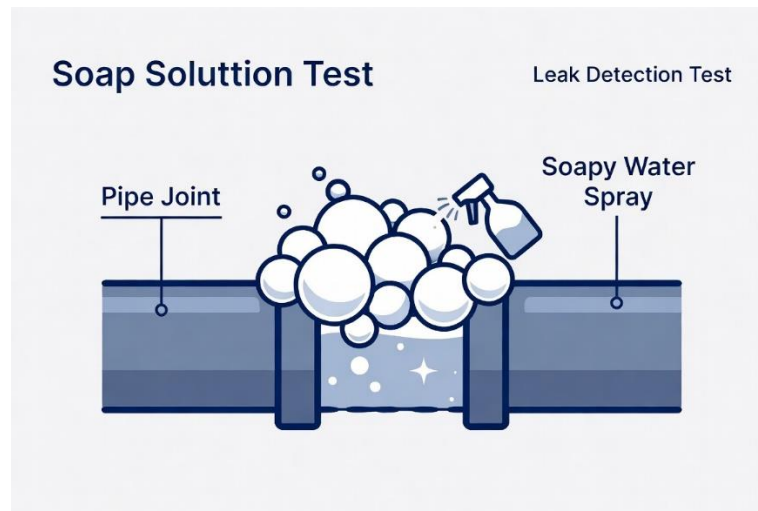


Figure 2.1: Soap Solution Bubble Test on Pipe Joint

Workshop Scene:

[Generator] → Spark

[Light Switch] → Click → Possible spark

[Mobile Charger] → Overheating

[No Smoking Sign] ← Must be visible

Figure 2.2 Common Ignition Sources

- Common mistakes to avoid
 - Using a lighter or match to look for leaks
 - Ignoring small sparks from old wiring
 - Forgetting to put up “No Smoking” signs
 - Thinking “it is only a small leak, nothing will happen”
- *Brainstorming Questions:*
 1. Why is hydrogen more dangerous to detect than LPG in a busy workshop?
 2. What are the most common ignition sources you see in your own workshop, and how can you control them when using hydrogen?

2.5. Chapter Summary

Hydrogen behaves very differently from fuels like *diesel* and *LPG*, so technicians must change their working habits to stay safe. It is a very light gas that rises quickly, has no color or smell, and burns with a flame that is almost invisible. Because of these properties, hydrogen leaks are difficult to detect and can become dangerous very quickly, especially in hot and poorly ventilated workshops common in *West Africa*.

The main risks of hydrogen include fast-spreading leaks, the presence of many ignition sources, and fires that are hard to see. Even a small leak can quickly mix with air and create a dangerous situation. Everyday items such as faulty wiring, diesel generators, phone chargers, switches, and extension boxes can easily produce sparks and ignite hydrogen without warning.

To reduce these risks, technicians must follow strict safety rules at all times. These include never using open flames to test for leaks, keeping electrical systems in good condition, using spark-proof tools when possible, and placing clear safety signs in the workplace. Most importantly, hydrogen work areas must always be treated as high-risk zones, where careful attention and proper procedures are required to prevent accidents and protect lives.

Chapter 3

H2-B2-3: Hydrogen Embrittlement and High-Pressure Risks

3.1. Understanding Hydrogen Embrittlement

Hydrogen embrittlement is a process where *hydrogen gas weakens metal*. This happens when very small hydrogen atoms enter the metal structure of pipes, tanks, or fittings. Normally, metals can *bend or stretch* under force. However, when hydrogen enters the metal, the metal becomes *hard and brittle* (easy to break), loses its ability to bend and can crack suddenly without warning, even under normal working conditions. This type of damage is **not visible from outside** and is different from rust or corrosion.

Hydrogen atoms are extremely small. Because of this, they can:

- Move inside the metal easily.
- Build up inside the structure.
- Cause *internal cracks* that grow quickly when the metal is under pressure or stress.

In many workshops, technicians reuse materials such as old LPG cylinders and air-compressor pipes. Although these materials may look strong, they are ***not designed for hydrogen use*** and can fail unexpectedly.

👉 Therefore, it is very important to ***use only hydrogen-rated materials***.

Practical Example:

A workshop changes from LPG to hydrogen use. Old steel pipes are reused to save cost. After some months, a pipe suddenly cracks during normal operation, causing a hydrogen leak and creating a serious fire risk.

Check-for-Understanding

Question: Why can a metal pipe appear strong but fail when used with hydrogen?

Answer: Because hydrogen enters the metal and makes it brittle, reducing its ability to withstand stress.

Hydrogen affects materials over time. Figure 3.1 illustrates how hydrogen affects strong metal pipe when it is added into the pipe. Hydrogen embrittlement:

- Hydrogen weakens metals like steel

- Pipes and fittings may crack suddenly

Old gas pipes may not be safe for hydrogen use.

→ Always check material compatibility.

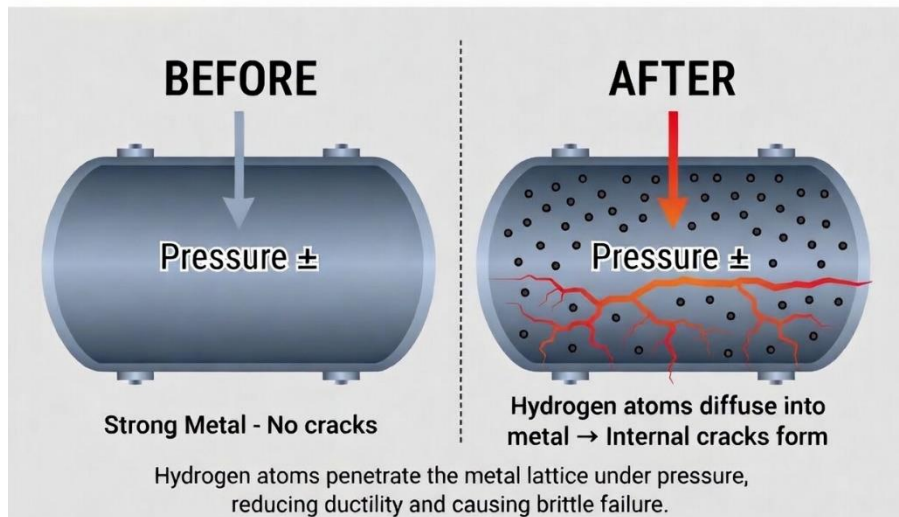


Figure 3.1 Hydrogen Embrittlement in a pipe, before and after Embrittlement Failure

The dots on Figure 3.1 represent hydrogen atoms entered the metal, which cannot be seen in real life. This highlights that **failure happens quickly**, even if no damage is visible before.

High-pressure risks:

- Hydrogen is often stored under pressure
- Sudden release can cause injury or noise shock

Safety practices:

- Inspect pipes regularly for cracks
- Avoid reusing old LPG or air compressor cylinders
- Use certified hydrogen-rated components

3.2. Risks of High-Pressure Hydrogen

Hydrogen gas is often stored under **high pressure** to reduce its volume and save space. However, this creates serious safety risks.

If a component such as a valve, pipe or tank fails suddenly, hydrogen can escape **very rapidly**.

This can cause:

- *A loud explosive sound* (noise shock)
- *Flying metal fragments* (projectiles)

- A *high-speed gas jet* that can injure people
- *Cold burns* due to rapid gas expansion
- Loss of balance or physical impact on workers

Even a *small leak* can be dangerous because:

- Hydrogen escapes with great force
- The gas is *invisible and odorless*
- It can ignite easily if it meets a spark

Practical Example:

A technician opens a cylinder not designed for hydrogen pressure. A fitting breaks suddenly, releasing gas with a loud bang. Small metal parts fly, and nearby workers are shocked.

Question: What can happen if high-pressure hydrogen equipment fails?

Answer: It can cause loud noise, flying fragments, and powerful gas jets that may injure workers or start fires.

3.3. Safety Practices to Prevent Failures

Preventing accidents in hydrogen systems depends on *proper materials, correct usage, and regular inspection*.

Key Safety Practices

1. Use the Right Materials

- Always use **hydrogen-certified components**.
- These materials are specially designed to resist embrittlement.

2. Avoid Reusing Old Equipment

- Do **not reuse LPG or air-compressor cylinders**.
- These are not designed for hydrogen and may fail quickly.

3. Perform Regular Inspections

Check equipment for:

- Cracks
- Rust
- Damaged joints or welds

Inspection schedule:

- **Visual check:** Weekly
- **Detailed inspection:** Monthly

4. Follow Safe Work Procedures

- Verify material compatibility before installation
- Use only approved hoses and fittings
- Do not modify equipment without expert guidance
- Keep inspection and maintenance records

Practical Example;

A technician installs a hydrogen system using new certified pipes. During routine inspection, a small crack is detected early and repaired before any accident occurs.

Check-for-Understanding

Question: Why should old LPG cylinders not be used for hydrogen storage?

Answer: Because they are not designed to resist hydrogen embrittlement and may fail under pressure.

3.4. Summary of the Chapter

Hydrogen embrittlement is a critical safety issue in hydrogen systems because it gradually weakens metals, making them brittle and prone to sudden failure. This damage occurs internally within the material and is often not visible from the outside, which increases the risk of unexpected cracks or breaks during normal operation. In addition, hydrogen is commonly stored under high pressure, and any failure in such systems can lead to serious hazards, including violent gas release, flying debris, and potential fires. The risk becomes even greater when incompatible or previously used equipment, such as old LPG or compressor components, is reused for hydrogen service. To ensure safety, it is essential to use only certified hydrogen-compatible materials and to carry out regular inspections, as these practices significantly reduce the likelihood of accidents and system failures.

CHAPTER 4

H2-B2-4: Safety Standards and Workplace Protocols

4.1. Basic Safety Standards for Hydrogen Workspaces

Every workshop or filling station that uses hydrogen must follow simple but strict safety rules. These rules protect workers and prevent fires or explosions. The four basic safety standards are:

1. proper ventilation,
2. clear safety signs,
3. correct use of Personal Protective Equipment (PPE), and
4. regular inspection schedules.

Proper ventilation is the most important. Hydrogen rises to the roof, so roof vents or fans must remove leaked gas before it builds up. Clear safety signs remind everyone of dangers and what to do. PPE protects the body from leaks, sparks, or sudden gas release. Routine inspections help find problems early before they become serious.

To make safety consistent, many countries follow *International Safety Standards*, such as:

- a) **ISO 22734:** – Safety requirements for hydrogen generators and systems.
- b) **IEC 60079:** – Rules for equipment used in explosive atmospheres (very important for hydrogen workshops).

Following these standards helps workshops in *West Africa* work safely and professionally. In West Africa, many workshops are small and hot. Following these standards turns a risky space into a safer workplace. Ignoring them can lead to accidents even with small amounts of hydrogen.

Practical Example/Scenario:

A technician in a small workshop in *Accra, Ghana* installs a hydrogen system for powering tools. He adds roof vents, puts up clear “Hydrogen in Use” and “No Smoking” signs, provides PPE for all workers, and creates a monthly inspection checklist. One day a small leak occurs, but the roof fan quickly removes the gas and no fire starts.

Question: Why is proper roof ventilation the most important basic safety standard for hydrogen?

Answer: Hydrogen is very light and rises quickly to the ceiling. Good ventilation removes the gas before it collects and creates a fire risk.

4.2. Personal Protective Equipment (PPE) for Hydrogen Work

Personal Protective Equipment (PPE) is clothing and gear that protects your body. When working with hydrogen, you must always wear the minimum PPE: safety boots, gloves, and eye protection.

Safety boots protect your feet from falling tools or cylinders. Gloves protect your hands from sharp edges, cold gas, or small leaks. Eye protection (safety goggles or face shield) protects your eyes from sparks or sudden gas release that can cause injury or temporary blindness.

PPE only works if you wear it properly every time and keep it in good condition. Replace damaged gloves or cracked goggles immediately. In hot West African workshops, choose light but strong PPE that workers will actually wear.

Practical Example/Scenario: In a hydrogen filling station in *Abidjan, Côte d'Ivoire*, a worker forgets to wear safety goggles while changing a cylinder. A small high-pressure release blows dust and gas into his eyes. He suffers eye irritation and cannot work for two days. After this, the supervisor makes daily PPE checks part of the morning routine.

Question: What is the minimum PPE every technician must wear when working with hydrogen?

Answer: Safety boots, gloves, and eye protection.

4.3. Workplace Protocols for West African Conditions

Workshops in West Africa face special challenges. In *Côte d'Ivoire*, many workshops are crowded with people and tools. Hydrogen systems must be kept in a separate, clearly marked area away from busy zones to reduce risk.

In *Nigeria*, power outages are very common. Technicians must know safe shutdown procedures, turn off hydrogen equipment safely and ventilate the area before leaving. Never leave hydrogen systems running without power or supervision.

Key daily rules that everyone must follow:

- Always label hydrogen pipes and cylinders clearly with “Hydrogen” signs.
- Never store hydrogen cylinders near heat sources like generators or stoves.
- Always keep emergency exits clear, never block them with equipment or boxes.

These simple protocols help prevent small problems from becoming big accidents.

Real Accident Case Study (Lessons Learned): In 2022, a small hydrogen filling station in Europe had a serious fire. The emergency exit was blocked by empty cylinders, and workers could not escape quickly. The fire caused major damage and injuries.

Lesson Learned: Always keep emergency exits completely clear. A blocked exit can turn a small incident into a tragedy. This mistake can happen easily in crowded West African workshops.

Practical Example/Scenario: During a sudden power outage in *Lagos, Nigeria*, a technician quickly shuts down the hydrogen system following the posted procedure, opens the roof vents, and moves workers outside. Because emergency exits were kept clear and cylinders were properly labeled, everyone stayed safe and the workshop restarted without incident after power returned.

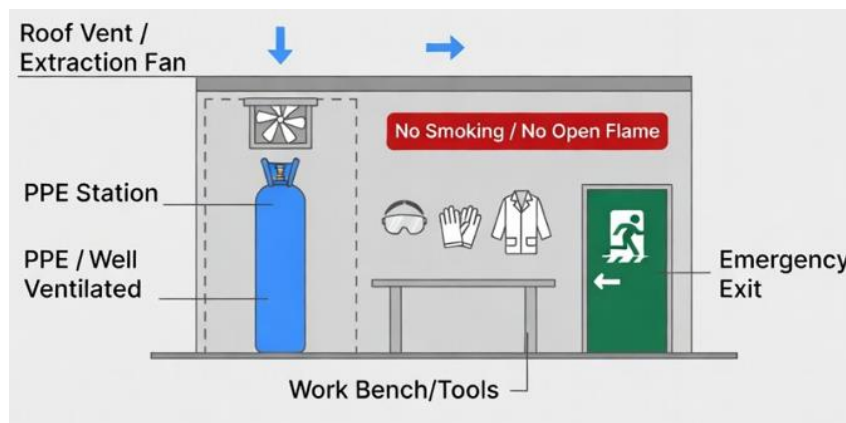


Figure 4.1 Proper workplace layout with Hydrogen system

Question: What should a technician do first during a power outage when hydrogen equipment is operating?

Answer: Follow the safe shutdown procedure, turn off the equipment safely, and ventilate the area.

4.4. Chapter summary

Every hydrogen workspace must follow essential safety practices to reduce risks and ensure smooth operation. Proper ventilation, clear warning signage, the use of personal protective equipment (PPE), and regular inspections are fundamental requirements in any hydrogen environment. Workers should always wear basic PPE, including safety boots, gloves, and eye protection, to minimize injury. In busy or crowded workshops, such as those found in Côte d'Ivoire, hydrogen systems should be kept separate from other activities to avoid accidental

interference. It is also important to prepare safe shutdown procedures, especially in areas like Nigeria where power outages are common, to prevent uncontrolled situations. Additionally, all hydrogen lines must be clearly labeled, cylinders should be stored away from heat sources, and emergency exits must always remain unobstructed. By following proper safety protocols and maintaining good daily work habits, most hydrogen-related accidents can be effectively prevented.

End-of-Chapter Review Questions

I. True or False

1. In a hot workshop in Senegal, you only need to check for hydrogen leaks at floor level because hydrogen is a heavy gas.
2. It is safe to store hydrogen cylinders near a diesel generator or any heat source as long as they are labeled.

II. Multiple Choice

1. You are working in a crowded workshop in Abidjan, Côte d'Ivoire. What is the safest way to set up the hydrogen system?
 - A. Place the hydrogen cylinder in the middle of the busy working area
 - B. Keep the hydrogen system in a separate, clearly marked area away from people
 - C. Put the cylinder near the door for easy access
 - D. Store it next to the generator to save space
2. A technician in Lagos, Nigeria is about to start work on a hydrogen-powered generator. Which PPE must he wear at minimum?
 - A. Only rubber boots
 - B. Safety boots, gloves, and eye protection
 - C. A face mask and normal clothes
 - D. Helmet and ear plugs only
3. You notice that the emergency exit in your workshop is blocked by toolboxes and spare parts. What is the correct action?
 - A. Leave it as it is because you are very busy
 - B. Immediately clear the exit and make sure it stays free at all times
 - C. Block it only during the day and clear it at night
 - D. Put a sign saying "Exit blocked – use window"

III. Practical Scenario Question

1. During a sudden power outage at a workshop in Accra, Ghana, the hydrogen backup system is still running. What should the technician do first?
2. Draw a simple sketch of a safe workshop layout for hydrogen use (or describe it in words). Label at least four important safety features.

CHAPTER 5

Leak Detection Basics and Emergency Response (H2-B2-5)

5.1 Introduction to Leak Detection

Learning Objectives

By the end of this chapter, learners will be able to:

- Explain why hydrogen leak detection is important
- Identify simple and affordable leak detection methods
- Describe emergency response steps during a hydrogen leak
- Apply basic safety practices in real workshop situations

5.1. Introduction

Hydrogen is a special gas that you cannot see and you cannot smell. It is also highly flammable, which means it catches fire very easily. Because hydrogen is invisible and has no smell, it is very difficult to know when there is a leak. A small hydrogen leak can spread quickly through the air. If it meets any spark, flame, or hot surface, it can suddenly cause a fire or even an explosion. This makes hydrogen different and more dangerous than fuels like diesel or LPG that you may already know.

That is why early detection of leaks is very important. If you find a leak quickly, you can stop it before it causes harm to people or damages equipment. Good safety habits can save lives and protect your workshop.

5.2. Basic Methods of Hydrogen Leak Detection

5.2.1. Soap Solution Test (Most Recommended Method)

The soap solution test is the easiest, cheapest, and most recommended way to find hydrogen leaks in workshops. It is the method most technicians in West Africa should use every day.

How it works:

Mix ordinary soap with clean water in a spray bottle or small container. Apply the soapy water to all pipe joints, valves, fittings, and connections. Then watch carefully. If you see bubbles forming and growing, it means hydrogen is leaking from that spot. The bubbles appear because the leaking gas pushes through the soap film.

This method is very popular because:

- It is very cheap – you only need soap and water
- It is simple and easy to use

- The materials are available in every local market

You do not need electricity or special tools. Even in rural workshops with no power, you can still carry out this test safely and quickly.

Important Tip: Always check high points (near the roof) as well as lower joints because hydrogen rises upwards.

5.2.2. Listening Method

The listening method is another simple way to check for hydrogen leaks.

How it works:

You listen carefully for a hissing or whistling sound coming from pipes, valves, or connections. This sound usually happens when hydrogen escapes under pressure.

Limitations:

This method is not very reliable in busy West African workshops. Workshops are often noisy because of generators, machines, and people working. Small leaks may also make very little or no sound, so you can easily miss them.

Because of these problems, the listening method should only be used together with the soap solution test, never as the only method.

5.2.3. Portable Gas Detectors

Portable gas detectors are electronic devices that can find hydrogen in the air.

How it works:

You turn on the detector and move it near pipes, joints, and equipment. If hydrogen gas is present, the device gives an alarm – it makes a loud sound or flashes a light to warn you.

Advantages:

- It is more accurate than listening
- It can detect even very small leaks that you cannot see or hear

Limitations:

- Good detectors can be expensive
- They need regular batteries and maintenance
- Users must be trained to use them correctly

In many small workshops, the soap solution test remains the main method. Portable detectors are useful as an extra safety tool when they are available.

5.3. Locally Available Leak Detection Tools (West African Context)

In many workshops across West Africa, you do not need expensive equipment to detect hydrogen leaks safely. Here are the most common and useful tools you can find locally:

- ***Soap + Water in a Spray Bottle:*** This is the cheapest and most common method. Soap and water are available in every market. It is the best tool for daily use.
- ***Recycled Spray Bottle or Bubble Applicator:*** You can make this yourself using an old spray bottle from home or the market. It is reusable and works very well with the soap solution.
- ***Basic Electronic Gas Sniffer:*** These small electronic detectors are sold by solar panel sellers and electronics shops in big towns. Some can detect several types of gas. They are more expensive but very useful if you can afford them.
- ***Ultrasonic Listening Devices (Optional):*** These are not common in small workshops, but they may be available in larger cities. They help hear very small leaks.

Practice Tip: Start by practising the soap solution test until you are very good at it. Later, when you reach a higher level, you can learn to use electronic detectors.

5.4. Emergency Response to Hydrogen Leaks

Key Rule

- ⊘ Never panic and never operate any electrical switches during a hydrogen leak.

When you discover a hydrogen leak, you must act quickly but calmly. Follow these simple steps in order:

Step-by-Step Emergency Response

1. ***Do Not Panic:*** Stay calm and think clearly. Panic can cause mistakes.
2. ***Stop the Source (If Safe):*** Close the valve or shut off the system, but only if you can do it without danger.
3. ***Avoid Sparks:*** Do NOT turn any electrical switches on or off. Do NOT use mobile phones near the leak. Do NOT use open flames or lighters.
4. ***Evacuate the Area:*** Move all people away to a safe distance.
5. ***Ventilate Immediately:*** Open all doors and roof vents so the hydrogen gas can escape into the air.
6. ***Call for Help:*** Inform your supervisor or call emergency services if needed.

Remember: Hydrogen rises to the roof, so opening high vents is very important. Quick and correct action can prevent a small leak from becoming a big accident.

Illustrative Examples:

1. Solar-Hydrogen Cold Storage – Northern Nigeria. A tomato storage unit uses hydrogen energy.

Risks: Hydrogen leak near produce area; poor ventilation traps gas under roof.

Safety actions: Install roof vents or fans; place “No Smoking” and “Hydrogen in Use” signs; conduct daily leak checks with soap solution.

Why critical: A leak could ignite and destroy both produce and facility.

Lesson: Good ventilation and regular leak checks can prevent serious accidents.

2. Telecom Tower – Rural Ghana:

A telecom company in rural **Ghana** replaced old diesel generators with hydrogen fuel cells.

Situation: They started using hydrogen, but the old pipes from the diesel system were still in place.

New Risks:

- Invisible hydrogen leaks
- Old pipes becoming weak because of hydrogen embrittlement

Technician Actions:

- They replaced the old pipes with hydrogen-safe materials.
- They began checking high points (roof area) for leaks.
- They made sure there was good airflow around the equipment.

Lesson: When you change to new technology like hydrogen, you must also change your safety practices.

Class Activities and Brainstorming

1. *Discussion Question:* In a rural workshop with no electricity, which leak detection method is best? Why?
2. *Scenario Question:* What should you do first if you hear a hissing sound near a hydrogen cylinder?

👉 Encourage students to think before answering.

5.5. Daily Safety Checklist (Preparation for Practical Level)

Students should learn to follow this checklist:

1. Check all joints using soap solution
2. Inspect pipes for cracks or damage
3. Ensure ventilation systems are working

4. Confirm safety signs and PPE availability
5. Ensure exits are clear

5.6. Chapter Summary

Hydrogen is a gas that you cannot see or smell, but it can catch fire very easily, which makes it dangerous. If it leaks, it is hard to notice without tools, but simple methods like using a soap solution can help find leaks because bubbles will form. Since hydrogen is very light, it rises upward, so good ventilation at higher points is important to keep it from building up. In case of an emergency, people should act quickly but stay calm and follow safe procedures. Also, some old materials can become weak when exposed to hydrogen, so they may break easily. By following proper safety rules and precautions, most accidents involving hydrogen can be avoided.

End-of-Chapter Review Questions

Multiple Choice

1. Hydrogen flames are:
 - A. Bright yellow
 - B. Blue and visible
 - C. Nearly invisible in daylight
 - D. Green
2. Hydrogen gas usually collects:
 - A. Near the floor
 - B. In water
 - C. Near the roof
 - D. Inside pipes only
3. Safe leak detection method:
 - A. Using a lighter
 - B. Smelling gas
 - C. Soap solution
 - D. Touching pipe

Short Answer

4. Why is ventilation important?
5. What is hydrogen embrittlement?

Practical Scenario

6. Write a 4-step daily safety checklist for a hydrogen system.

H2-B3: Fundamentals of Hydrogen Production Technologies

Learning Objectives:

By the end of this chapter, learners will be able to:

- Identify major hydrogen production methods (SMR, electrolysis, biomass, coal gasification)
- Distinguish hydrogen types by color (grey, blue, green, brown)
- Explain basic efficiency and cost factors
- Choose the most suitable production method for a rural village in West Africa based on available resources

Chapter 1

Main Hydrogen Production Methods (H2-B3-1)

1.1. Introduction: Why Hydrogen Matters?

Hydrogen is a clean energy carrier. This means it can store and transport energy to be used later for making electricity, heat, or fuel for machines and vehicles.

Hydrogen is very important because it can replace diesel and other fossil fuels that we use every day. It can also store energy from solar panels and wind turbines for use when the sun is not shining or the wind is not blowing. When hydrogen is used, it produces no smoke or harmful gases, only clean water comes out.

In Africa, especially in West African countries like Senegal, Nigeria, Ghana, and Côte d'Ivoire, hydrogen can bring big benefits. It can provide reliable power to remote villages that have no electricity. It can help reduce the amount of expensive fuel we import from other countries. Most importantly, we can produce hydrogen using our own local resources such as strong sunlight and farm waste (biomass).

1.2. Main Hydrogen Production Methods (H2-B3-1)

There are four main ways to produce hydrogen. Each method uses different raw materials and has different costs and environmental effects. Let us look at them one by one.

1.2.1. Steam Methane Reforming (SMR)

SMR is the most common method used in the world today. In this process, natural gas is mixed with steam at very high temperature to produce hydrogen.

Inputs: Natural gas + Water (as steam)

Outputs: Hydrogen (H₂) + Carbon dioxide (CO₂)

- Efficiency: 60–75%
- Cost: About \$1–2 per kg

Advantages:

- It is the cheapest way to produce hydrogen today
- It is already used in many industries

Disadvantages:

- It releases a lot of carbon dioxide (CO₂), which pollutes the air
- It needs natural gas, which is not available in every country

Local Context: Nigeria has large supplies of natural gas, so SMR is realistic for large-scale production in the country right now.

1.2.2. Electrolysis

Electrolysis uses electricity to split water into hydrogen and oxygen. It is like using electricity to “break” water apart.

Inputs: Water + Electricity

Outputs: Hydrogen + Oxygen

- Efficiency: 55–75%
- Cost: About \$3–6 per kg

Advantages:

- It is very clean if the electricity comes from solar or wind power
- It is very suitable for sunny countries in West Africa

Disadvantages:

- It is more expensive than SMR today
- It needs a reliable source of electricity

Local Context: Senegal and Ghana have plenty of sunshine, so solar-powered electrolysis has very good potential for producing clean (green) hydrogen.

1.2.3. Biomass Hydrogen

This method uses organic waste from farms and households to produce hydrogen.

Inputs: Crop waste such as rice husks, cassava peels, and palm waste

Outputs: Hydrogen + Small amount of emissions

- Efficiency: 40–50%
- Cost: About \$2–4 per kg

Advantages:

- It uses waste materials that are usually thrown away
- It is good for rural and farming areas

Disadvantages:

- Lower efficiency compared to other methods
- Needs good organisation to collect the waste regularly

Local Context: Côte d'Ivoire, Benin, and parts of Ghana produce a lot of agricultural waste, making biomass hydrogen a promising option for villages.

2.4. Coal Gasification

In this method, coal is heated at very high temperatures to produce hydrogen.

Inputs: Coal

Outputs: Hydrogen + Large amount of CO₂

Efficiency: 45–55%

Cost: About \$1–2 per kg

Advantages:

- It is cheap where coal is available

Disadvantages:

- It produces a lot of pollution and CO₂
- It is not good for a clean energy future

Local Context: This method is not widely used in West Africa because most countries do not have large coal deposits and prefer cleaner options.

1.3. Summary of the Chapter

In this chapter, we learned that hydrogen can be produced in four main ways:

- Steam Methane Reforming (SMR) – cheapest but produces pollution
- Electrolysis – clean when using renewable electricity, good for sunny areas
- Biomass Hydrogen – uses farm waste, suitable for rural West Africa

- Coal Gasification – cheap but very polluting

Each method has its own advantages, cost, and effect on the environment. For West Africa, electrolysis using solar power and biomass from crop waste are the most promising methods because they use our local resources and support cleaner energy goals. Choosing the right production method depends on what resources are available locally, sunlight, natural gas, or farm waste.

Chapter 2

Hydrogen Color Classification

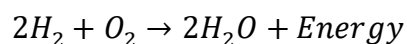
Hydrogen is often classified using **color codes** based on the production method and environmental impact. We use special “colors” to describe how clean or dirty hydrogen is. These colors do not show the real color of the gas. Instead, they tell us how much pollution, especially carbon dioxide, is produced when the hydrogen is made. Understanding these color codes is very important for as it helps us choose the cleanest and most suitable ways to produce hydrogen using our local resources.

Hydrogen is commonly grouped into three main types based on how it is produced and its impact on the environment. These are Green Hydrogen, Blue Hydrogen, and Grey Hydrogen. Figure 2.1 shows these classifications, and Table 2.1 Presents comparison of hydrogen types in which production method, main raw material, pollution level, cost and suitability for West Africa. The production processes of each the Hydrogen type are detailed as follows.

2.1.1. Green Hydrogen

Green hydrogen is produced using *renewable energy sources*. It can be produced by water electrolysis which is powered by solar energy, wind energy or hydroelectric power.

Process:



Advantages:

- zero carbon emissions
- sustainable energy source
- supports climate goals

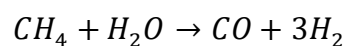
2.1.2. Blue Hydrogen

Blue hydrogen is produced from *natural gas*, but the carbon dioxide emissions are captured and stored.

Production process:

- *Steam Methane Reforming (SMR) + Carbon Capture and Storage (CCS)*

Reaction:



Advantages:

- lower emissions than grey hydrogen
- transitional technology toward clean hydrogen

2.1.3. Grey Hydrogen

Grey hydrogen is the most common hydrogen production method today.

- Production process: *Steam Methane Reforming without carbon capture.*
- Disadvantage: significant CO₂ emissions

Approximately 95% of global hydrogen production is currently grey hydrogen.

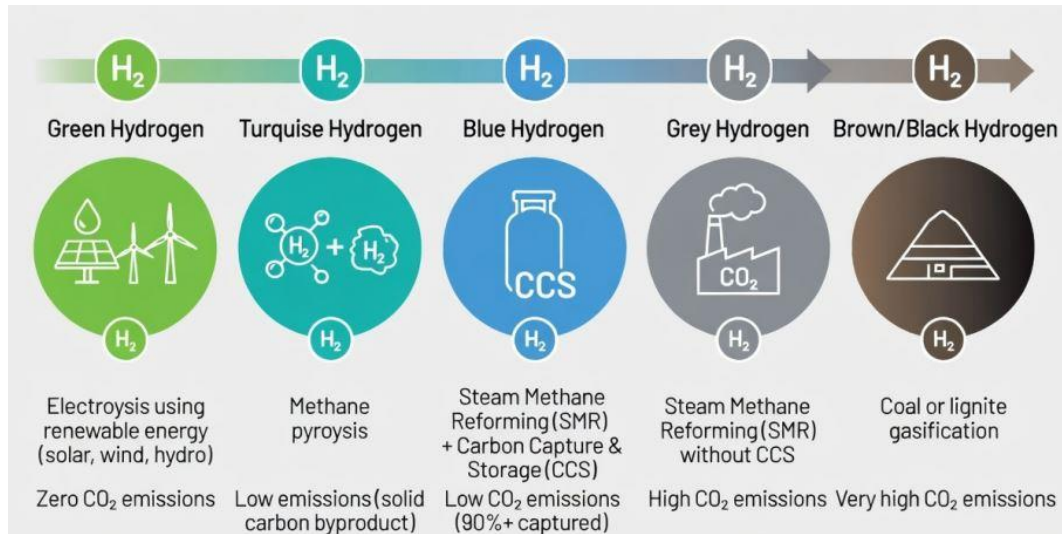


Figure 2.1 Hydrogen Color Classification Chart

Table 2.1. Detailed comparison of hydrogen type with their production and pollution level

Hydrogen type	Production Method	Main Raw Material	Pollution Level	Suitability for West Africa
Brown/Black Hydrogen	Coal Gasification	Coal	High	Low
Grey Hydrogen	SMR	Natural Gas	High	Moderate
Blue Hydrogen	SMR with CCS	Natural Gas	Medium	Moderate to High
Green Hydrogen	Electrolysis using Renewable Energy	Water	Very Low	High

2.2. Why Hydrogen Colors Matter in West Africa

In West Africa, we have strong sunlight almost all year. This makes green hydrogen very promising for countries like Senegal, Ghana, and Côte d'Ivoire.

Using green hydrogen helps us:

- Reduce dependence on imported diesel
- Create cleaner energy for villages
- Fight climate change

Grey and brown hydrogen may be cheaper now, but they add to pollution. Blue hydrogen is a middle step, but green is the long-term goal for Africa. Figure 2.2 depicts hydrogen color ladder, in which a simple vertical ladder showing the four colors from top to bottom:

- Brown (highest pollution) → Grey → Blue → Green (zero pollution).

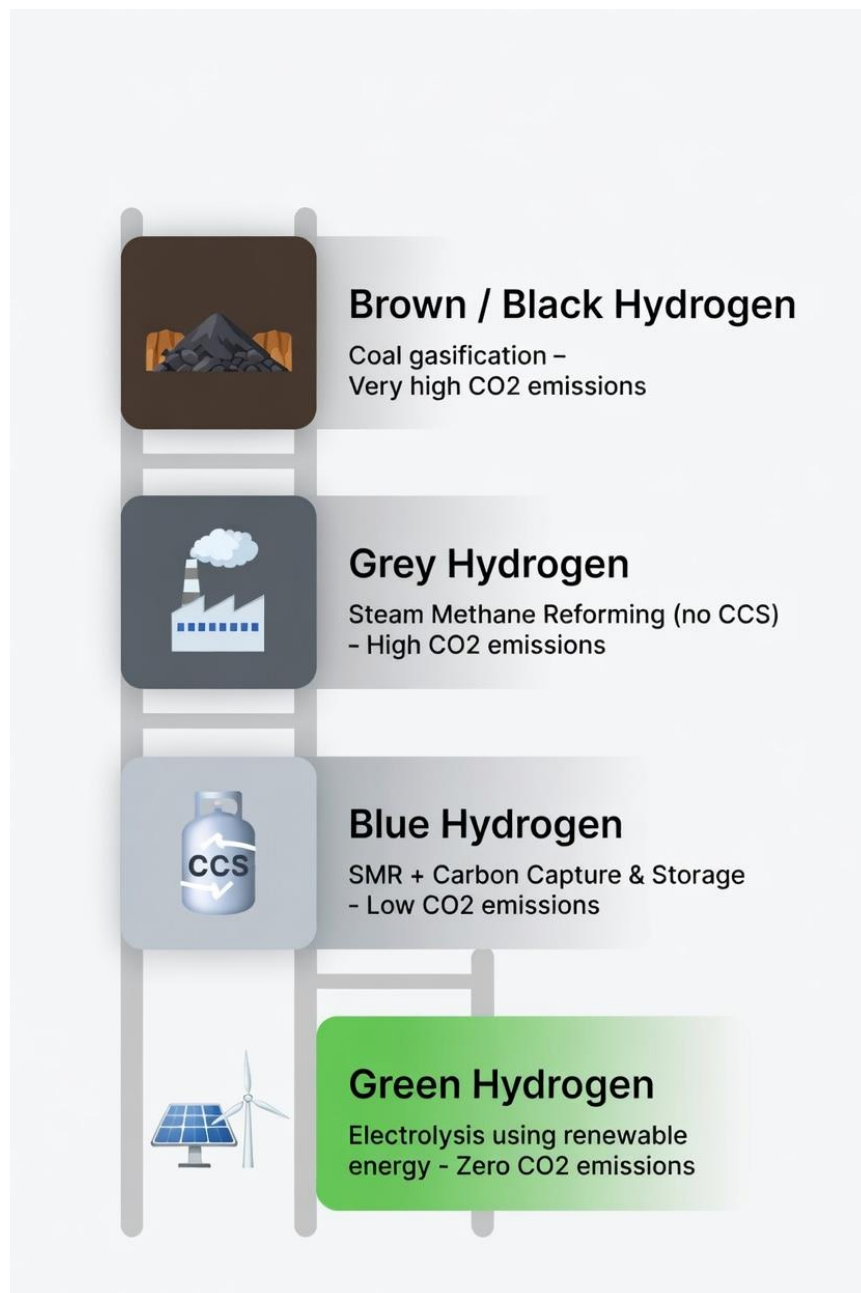


Figure 2.2 Hydrogen color ladder

Each step has a small icon (coal, gas, gas + capture, solar panel) and a short note on emissions. This helps students visually understand the order of cleanliness.

In general, countries with large renewable energy potential (Sub-Saharan and West Africa countries) could become green hydrogen producers.

Examples include:

- Solar-rich regions (Sahel)
- Wind-rich coastal regions
- Hydropower regions

This could create new energy industries and jobs.

West Africa receives strong sunlight throughout the year, making **green hydrogen** a highly suitable energy option. Countries such as Mali, Burkina Faso, and Niger have excellent solar potential, which can be used to power electrolyzers and produce hydrogen. Figure 2.3 shows how solar panels in a sunny West African village can be connected to an electrolyzer to generate hydrogen, with only clean water vapor released as a byproduct. Local water sources, including rivers and boreholes, can support this process. Using green hydrogen can reduce dependence on diesel fuel and improve energy independence, while also meeting both rural and urban energy needs.

In addition, there is strong potential for **bio-hydrogen** production. Agricultural waste materials, such as cassava peels and rice husks, can be converted into hydrogen. This not only helps reduce environmental pollution but also creates job opportunities in local communities.

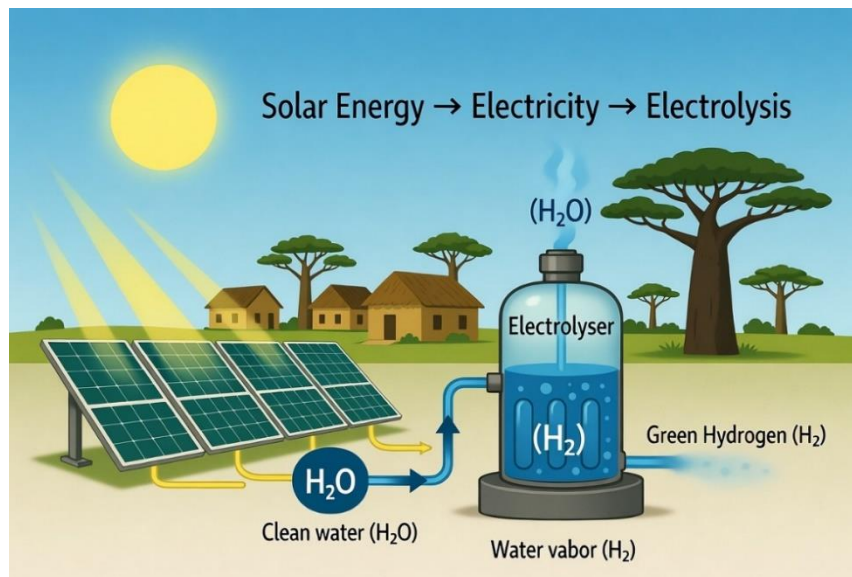


Figure 2.3 Green Hydrogen from Sunlight in West Africa

2.3.Chapter Summary

Hydrogen is often classified by colors to indicate how environmentally friendly its production is. Grey hydrogen is the most affordable option but also the most polluting, while blue hydrogen offers a cleaner alternative by capturing the carbon dioxide produced during its creation. Green hydrogen is considered the cleanest form because it is generated using renewable energy sources such as solar and wind power. In contrast, brown hydrogen is the most harmful to the environment, as it is produced from coal. For West Africa, green hydrogen represents the most promising option for the future due to the region's abundant sunshine and availability of agricultural waste resources.

End-of-Chapter Review Questions

I. Multiple Choice Questions

1. Which type of hydrogen is the cleanest?
 - A. Grey hydrogen
 - B. Blue hydrogen
 - C. Green hydrogen
 - D. Brown hydrogen
2. Grey hydrogen is mainly produced from:
 - A. Coal
 - B. Solar power
 - C. Natural gas

D. Farm waste

3. Why is green hydrogen very suitable for Senegal and Ghana?

- A. Because these countries have a lot of coal
- B. Because they have strong sunshine for solar power
- C. Because they have no sunlight
- D. Because it is the most expensive

II. Short Answer Questions

4. Explain in one or two sentences the difference between grey hydrogen and blue hydrogen.

5. Why do we say green hydrogen is the best for the future of West Africa?

III. Practical Question

6. A village in Northern Nigeria wants to produce hydrogen. They have plenty of sunlight but limited money. Which color of hydrogen would you recommend and why? (Answer in 3–4 sentences)

Chapter 3

Basic Techno-Economic Considerations (H2-B3-3)

Learning Objectives

By the end of this chapter, you will be able to:

- Define “Levelized Cost of Hydrogen” (LCOH) in simple terms.
- List the three main cost drivers for any hydrogen production method.
- Compare the relative capital costs (CAPEX) and operational costs (OPEX) of grey versus green hydrogen.
- Identify which production method is cheapest today and which is expected to be cheapest by 2030.

3.1. Why Economics Matter for Technicians

As a TVET technician or apprentice working in a hydrogen plant, your daily job is hands-on: you operate valves, check pressures, maintain electrolyzers, or troubleshoot reformers. But economics decides whether that plant even gets built and how long it stays open. Think of it like owning a small delivery business. You can buy the best truck (technology), but if the fuel costs more than what customers pay for deliveries, the business fails. In hydrogen production the “fuel” is the input (natural gas or electricity) and the “delivery” is the kilograms of H₂ you sell.

Every production method has *inputs* that cost money and an *output* (H₂) that must be sold at a profit. If your maintenance work reduces downtime or improves efficiency, you directly lower the cost per kg of hydrogen. That is why technicians must understand basic costs, not to become accountants, but to make smarter decisions on the shop floor.

Grey hydrogen (from fossil fuels) is cheap today but produces CO₂. Green hydrogen (from renewable electricity) costs more now but creates no emissions. Understanding these differences helps you explain to your team why a plant might switch technologies in the future.

Brain storming questions:

1. *In your own words, why should a technician care about the cost of hydrogen production?*
2. *Give one real-world analogy (like the delivery truck) that explains why input costs matter.*

3.2. The Three Pillars of Hydrogen Cost: CAPEX, OPEX, and Capacity Factor

Every hydrogen production method rests on three simple pillars. Learn them once and you can compare any technology.

1. CAPEX (Capital Expenditure): – the upfront cost of building the plant and buying the equipment. Analogy: buying the delivery truck. High CAPEX means expensive electrolyzers or reformers.
2. OPEX (Operational Expenditure): – the day-to-day running costs (maintenance, labor, water, catalysts). Analogy: paying the driver's salary and servicing the truck.
3. Capacity Factor: – the percentage of time the plant runs at full power. Analogy: how many hours per year the truck is actually on the road instead of parked. A plant that runs 90 % of the time spreads its CAPEX over far more kilograms of H₂ than one that runs only 30 %.

These three pillars together decide the final cost per kilogram. Fossil-based plants usually have lower CAPEX but higher feedstock costs. Electrolysis plants have higher CAPEX but can use “free” sunshine or wind when the sun shines or wind blows.

Brain storming questions:

1. Name the three pillars of hydrogen cost.
2. Which pillar is like “how many hours the truck actually drives”?

3.3. Simple LCOH Formula

The Levelized Cost of Hydrogen (LCOH) is simply the average net cost to produce one kilogram of H₂ over the entire lifetime of the plant. It answers the question: “If I add up every dollar I spend and divide by every kilogram I make, what is the real cost per kg?”

No calculus needed. The plain-language formula is:

$$LCOH = \frac{\text{Total Lifetime Cost (\$)}}{\text{Total Lifetime H}_2 \text{ production (kg)}}$$

In everyday terms:

- Add up all CAPEX (spread over years), all OPEX, and all feedstock/electricity costs.
- Divide by the total kilograms of hydrogen the plant will produce during its 20–30-year life.

This number lets you compare SMR, electrolysis, or coal gasification on equal footing.

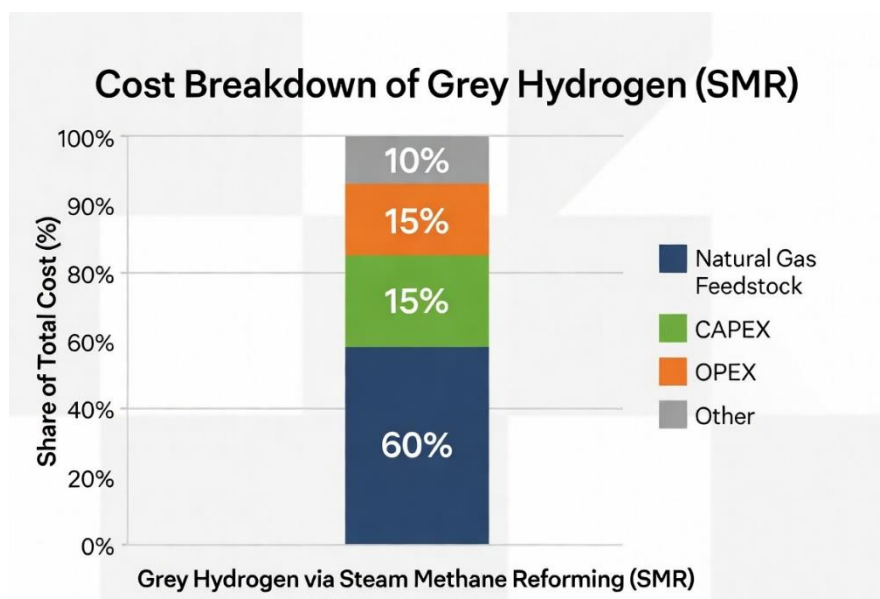


Figure 3.1 Cost Breakdown of Grey Hydrogen (SMR)

Table 3.1 presents comparative cost of Grey vs. Blue vs. Green Hydrogen in 2025–2026 cost ranges (USD per kg of H₂) for the main commercial methods. Other methods are noted briefly.

Production Method	Type	2025/6 Cost (USD/kg)	Main Cost Driver	Key Notes
Steam Methane Reforming (no CCS)	Grey	1.5 – 2.5	N. gas (60%)	Cheapest today, high CO ₂ emissions
SMR + Carbon Capture & Storage	Blue	2.0 – 3.5	N. gas + CCS	Lower emissions, extra cost for capture
Alkaline / PEM Electrolysis	Green	4.0 – 8.0	Electricity (70 %)	Zero emission if renewable power
Coal Gasification	Fossil (grey/black)	2.0 – 4.0	Coal feedstock	Common in Asia, very high CO ₂
Biomass Gasification	Emerging /Renewable	3.0 – 6.0	Biomass feedstock	Renewable but supply varies
Solid Oxide Electrolysis (SOEC)	Green (advanced)	3.5 – 7.0	Electricity + heat	Higher efficiency, needs high temperature
Thermochemical Water Splitting	Emerging	Not commercial yet	High-temperature heat	Research stage, potential low cost later

Cheapest today: Grey SMR.

Expected cheapest by 2030: Green electrolysis in regions with very cheap renewable electricity (projected 1–3 USD/kg).

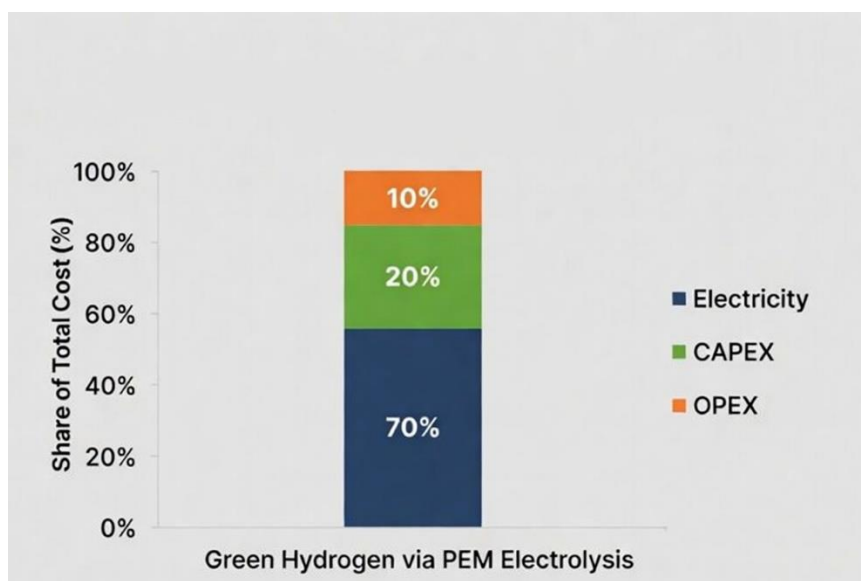


Figure 3.2 Cost Breakdown of Green Hydrogen (PEM Electrolysis)

3.4. Key Variable Impact: Electricity Price vs. Natural Gas Price

Electricity price is the “make-or-break” factor for green hydrogen. Every extra dollar per MWh adds roughly 0.05–0.07 USD to the cost of each kg of H₂. Natural gas price dominates grey and blue hydrogen. A big jump in gas price (e.g., from \$3 to \$8 per MMBtu) can make SMR more expensive than electrolysis in some countries.

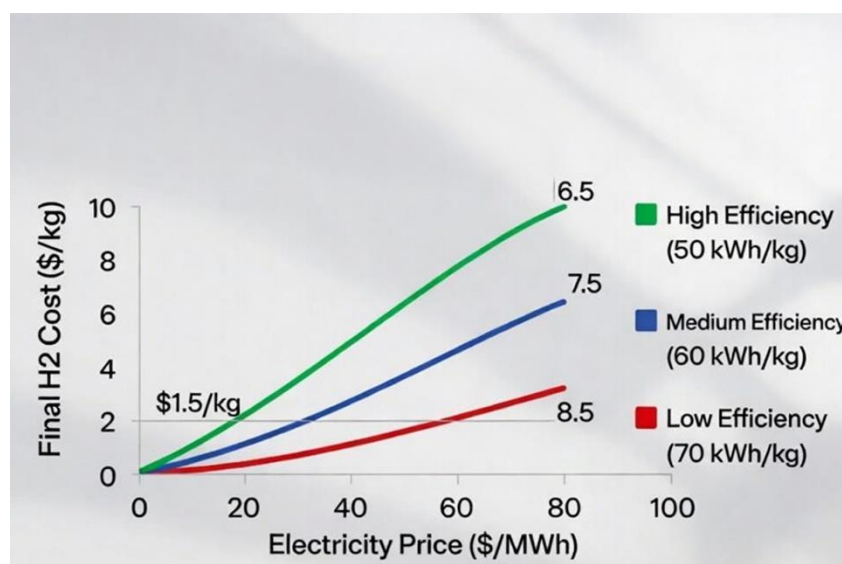


Figure 3.3 Impact of Electricity Price on Green Hydrogen Cost

3.5. Scale Economies: Why Bigger Is Cheaper per kg

A 1 MW electrolyzer is more expensive per kilogram than a 100 MW plant. Why? Many costs (control systems, civil works, engineering) are “fixed” they do not grow proportionally with size. Spreading those fixed costs over 100 times more hydrogen makes each kilogram cheaper.

Example: Doubling plant size might increase total CAPEX by only 70 %, not 100 %. This is why governments and companies now plan gigawatt-scale hydrogen hubs instead of small demonstration plants.

Brain storming questions:

1. If electricity costs \$30/MWh instead of \$70/MWh, will green hydrogen become cheaper or more expensive?
2. True or false: A larger plant always has lower cost per kg because of scale economies.

3.6. Regional Advantages

The “winning” technology depends on what your country has in abundance:

- Middle East & North Africa → Solar + Electrolysis wins (very cheap solar electricity).
- USA Gulf Coast & parts of Russia → Natural gas + SMR (± CCS) wins (cheap feedstock).
- Scandinavia, UK, Scotland → Wind + Electrolysis wins (strong offshore wind).
- East Africa & Ethiopia → Huge solar and hydropower potential makes green electrolysis very attractive in the coming decade.

Countries with both cheap renewables and good ports can export green hydrogen or ammonia and create thousands of technician jobs.

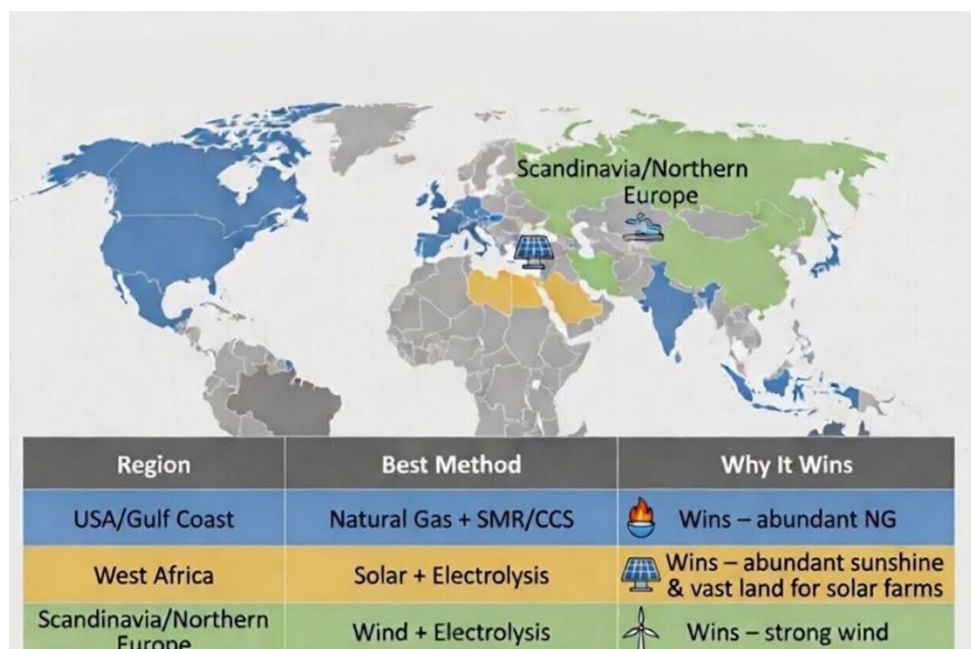


Figure 3.4: Regional Winners for Hydrogen Production

Activity:

Practical Classroom Activity (30–45 minutes)

Given electricity at \$0.05/kWh (= \$50/MWh) and a PEM electrolyzer efficiency of 65 % (≈ 60.6 kWh per kg H_2):

- 1. Calculate the electricity cost component per kg of H_2 .*
- 2. Add \$1.5/kg for CAPEX + OPEX (typical fixed costs).*
- 3. What is the total estimated LCOH?*
- 4. Repeat the calculation if electricity drops to \$0.02/kWh (common in sunny regions by 2030).*

Discuss in groups: Would this plant be competitive with grey hydrogen at \$2/kg?

3.7. Chapter summary

The Levelized Cost of Hydrogen (LCOH) represents the average cost of producing hydrogen over its entire lifetime, measured per kilogram. This cost is determined by three main factors: capital expenditure (CAPEX), operating expenditure (OPEX), and the capacity factor, which reflects how efficiently production assets are used. Currently, grey hydrogen produced through steam methane reforming (SMR) is the cheapest option, costing around \$1.5–2.5 per kilogram. However, green hydrogen produced through electrolysis is more expensive at present but is expected to become competitive, or even the cheapest option, by 2030 in regions with strong renewable energy resources. The price of electricity is the most important factor influencing the cost of green hydrogen, while natural gas prices primarily affect the cost of grey and blue hydrogen. Additionally, building larger production plants and utilizing favorable regional resources, such as abundant solar, wind, or low-cost natural gas, can significantly reduce overall costs.

Review Questions

1. What does LCOH stand for and what does the simple formula calculate? (Short answer)
2. Which of the following is NOT one of the three main cost pillars? (a) CAPEX (b) Electricity price (c) OPEX (d) Capacity Factor
3. In the cost breakdown of green hydrogen, what is usually the largest single component?
4. True or false: A 100 MW electrolysis plant will have a lower cost per kg than a 1 MW plant because of scale economies.
5. Which production method is cheapest today and which is projected to improve the most by 2030?

(Answers: 1. Levelized Cost of Hydrogen – total lifetime costs divided by total kg produced; 2. b; 3. Electricity; 4. True; 5. Grey SMR today; green electrolysis by 2030 in renewable-rich regions.)

Chapter 4

H2-B3-4: Overview of Emerging Technologies

Learning Objectives

By the end of this chapter, you will be able to:

- Name three emerging hydrogen production methods that do not rely on fossil fuels or fresh water.
- Explain the main advantage of methane pyrolysis over steam methane reforming (no CO₂ emissions, solid carbon by-product).
- Describe why thermochemical cycles require very high temperatures (>800°C) and which energy sources can provide that.
- Identify at least one current limitation (e.g., low efficiency, short lifetime, high cost) for each emerging technology.
- State which emerging technology is closest to commercial deployment (AEM electrolysis or methane pyrolysis).

4.1. What Makes a Technology “Emerging”?

Not every new idea is ready for your workshop tomorrow. Engineers use a simple scale called Technology Readiness Level (TRL) to measure how close an idea is to real-world use.

Think of TRL like cooking a new recipe:

- TRL 1–3: You read the recipe and test it once in your own kitchen (lab scale).
- TRL 4–6: You cook it in a small restaurant kitchen and invite friends to taste it (pilot plants).
- TRL 7–9: You open a big canteen that serves 10,000 meals a day without mistakes (commercial scale).

Most “emerging” technologies sit between TRL 3 and 7. They show great promise on paper or in small tests, but they are not yet cheaper, more reliable, or easier to operate than grey or green hydrogen. They are important for the long-term future because they can use waste, seawater, or sunlight directly and produce almost zero emissions.

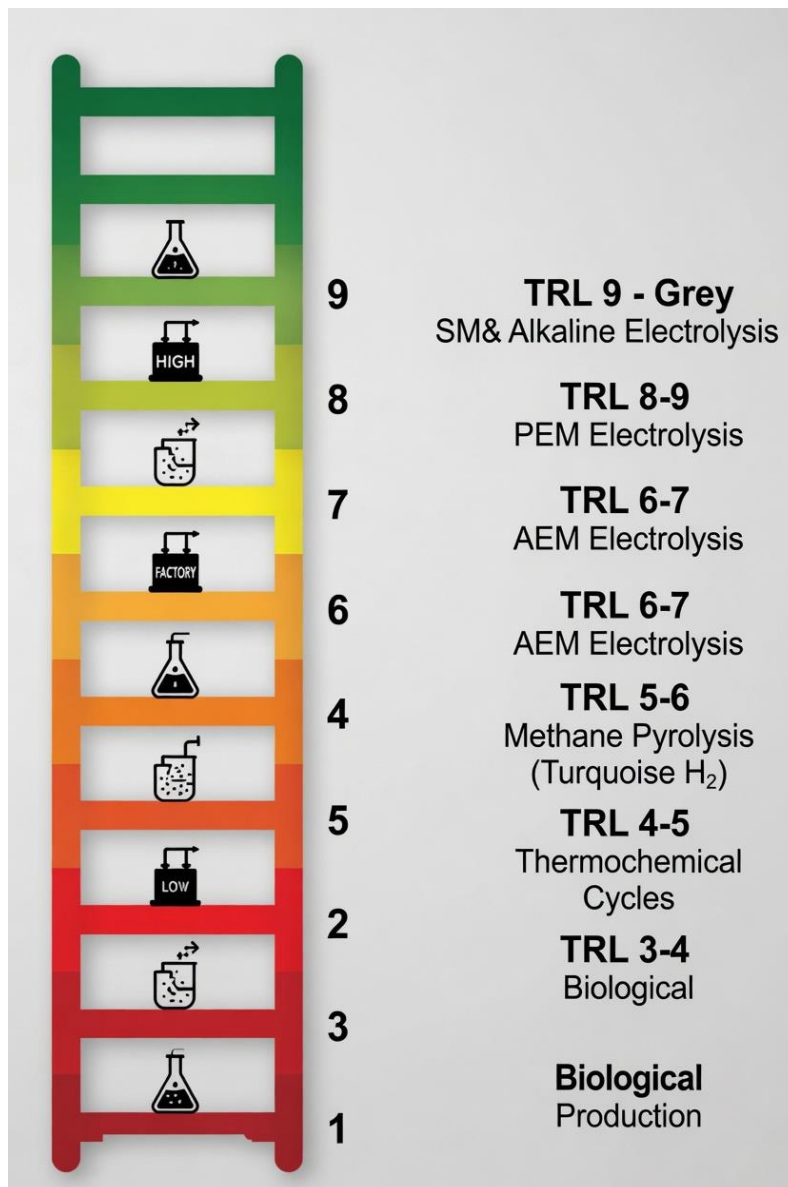


Figure 4.1 Technology Readiness Level (TRL) Ladder for H₂ production

4.2. Methane Pyrolysis/Plasma-Based H₂ (Turquoise Hydrogen)

This method heats methane (CH₄ from natural gas) in a plasma torch to split it into hydrogen gas and solid carbon powder, no oxygen, no CO₂ chimney. Main advantage over normal steam methane reforming (SMR): instead of greenhouse gas, you get valuable solid carbon that can be sold for tires, batteries, or construction materials. It still uses natural gas as feedstock, but the plant can be almost emission-free if the carbon is not burned. Several pilot plants (TRL 5–6) are running in 2025–2026. Limitation today: plasma torches use a lot of electricity, and carbon can build up inside the reactor and cause shutdowns for cleaning.

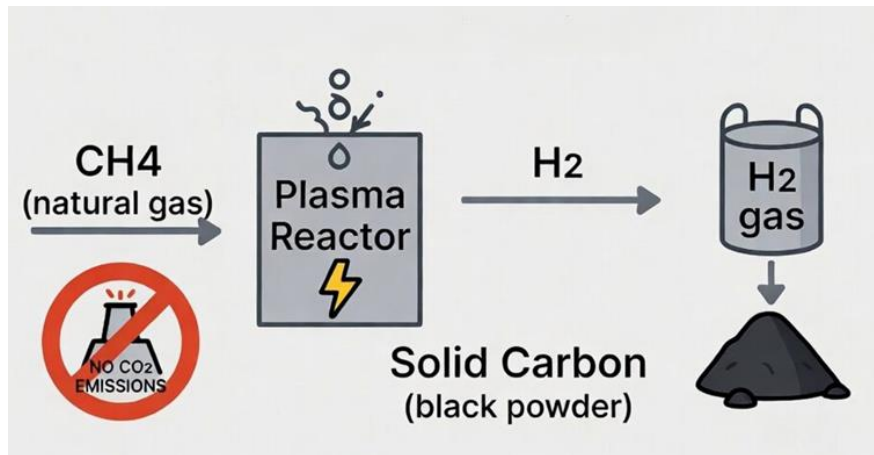


Figure 4.2 Simplified Flow Diagram of Methane Pyrolysis

Brain storming questions

1. Why is solid carbon a better by-product than CO_2 ?
2. Is methane pyrolysis fully “green” or still partly fossil-based?

4.3. Thermochemical Water Splitting

Instead of electricity, these processes use very high heat ($>800^\circ\text{C}$) to drive chemical reactions that split water into H_2 and O_2 . The chemicals are recycled in a closed loop (like a chemical merry-go-round). Example: sulfur-iodine cycle or metal-oxide cycles. Heat can come from concentrated solar towers or next-generation nuclear reactors.

- Advantage: no expensive electrolyzer membranes and potentially very high efficiency when cheap heat is available.
- Limitation: materials must survive extreme heat and corrosive chemicals; current systems are only at TRL 4–5 (small lab or very small pilots).

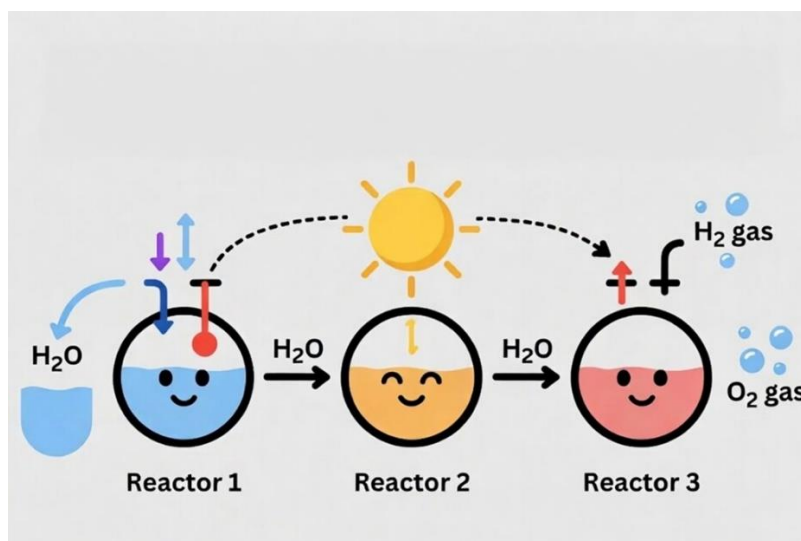


Figure 4.3: Cartoon of a Thermochemical Water Splitting Cycle

Brain storming questions

1. *Why do thermochemical processes need temperatures above 800 °C?*
2. *Name one free or low-cost heat source that could power them.*

4.4. Biological Routes

Hydrogen can also be produced naturally using living organisms such as bacteria, algae, or special enzymes. These methods are called *biological routes*. There are three main types:

- **Dark fermentation:** Bacteria break down waste materials (like organic waste) in the absence of light to produce hydrogen.
- **Photofermentation:** Bacteria or algae use sunlight to help produce hydrogen.
- **Microbial electrolysis cells:** Bacteria work with a small amount of electricity to split water and produce hydrogen at a low voltage.

These methods are useful because they can use waste materials and natural processes to produce clean energy.

- Advantage: they can use wastewater, food waste, or agricultural residues, no fresh water or fossil fuels needed.
- Limitation: very slow reaction rates and low yields. Current systems are still at TRL 3–4 (lab scale only).

Brain storming questions

1. *Name one biological method that does not need fresh water or fossil fuels.*
2. *Why are biological routes not yet used in big plants?*

4.5. Next-Generation Electrolysis: AEM and Ceramic Membranes

Alkaline and PEM electrolyzers are already used in industry today. However, new types are being developed to make hydrogen production cheaper and easier to use.

- **Anion Exchange Membrane (AEM) electrolysis:** This method works in an alkaline (basic) environment. It does not need expensive metals like platinum, so it can reduce cost. It is also easier to build in large sizes. It is still being tested but is close to being used commercially.
- **Proton-conducting ceramic membranes:** This method works at very high temperatures, similar to solid oxide systems. It can use waste heat from industries, which makes it more efficient.

These new technologies are among the most advanced of the emerging methods and are expected to be used commercially in the near future.

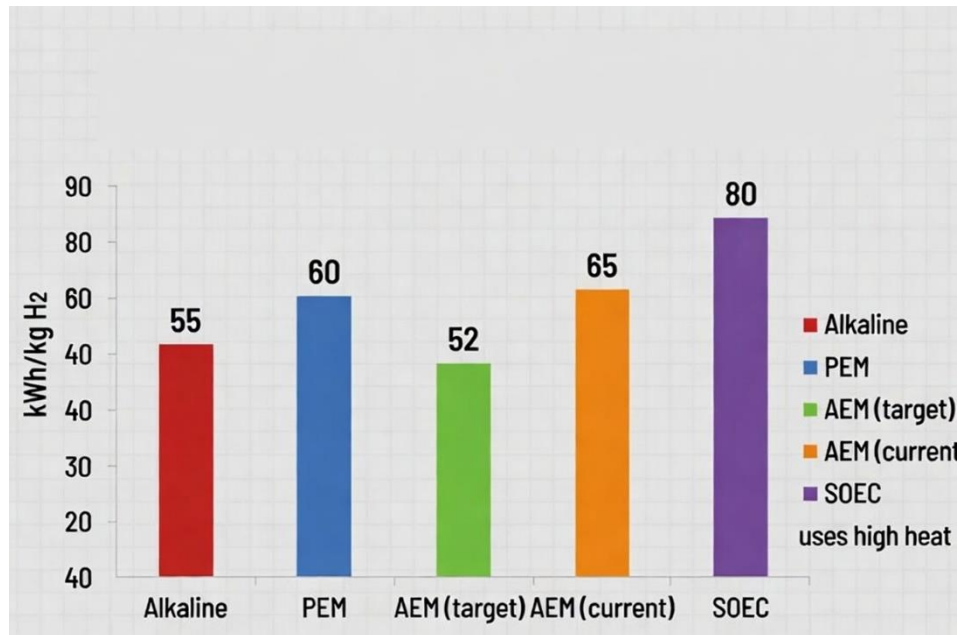


Figure 4.4 Comparison of Electrical Efficiency of various electrolysis technologies

4.6. Seawater and Waste-to-Hydrogen

These are new ways of producing hydrogen that help save water and reduce waste.

- **Direct seawater electrolysis:** This method uses seawater (ocean water) directly to produce hydrogen, without needing to first remove the salt. This is useful in dry countries where fresh water is limited. However, the salt can damage (corrode) the equipment quickly, which is still a challenge.
- **Waste-to-hydrogen:** This method produces hydrogen from waste materials such as plastic, old tyres, and household rubbish. Processes like gasification or pyrolysis are used to convert the waste into hydrogen. This helps reduce pollution and landfill while producing useful energy.

Both methods do not rely on fossil fuels or fresh water, making them good for a *circular economy* (where waste is reused). However, they are still being tested and are not yet widely used.

Brain storming questions

1. What is one big advantage of direct seawater electrolysis?
2. Why is waste-to-hydrogen good for the environment?

Table 4.1 Comparison of the main emerging technologies for H₂ production

Technology	TRL (2025/6)	Feedstock	Energy Input	Main Challenge
Methane Pyrolysis (Plasma)	5–6	Natural gas	Electricity (plasma)	Carbon fouling & high energy use
Thermochemical Cycles	4–5	Pure water	High heat (>800 °C)	Material durability at high temp
Biological Production	3–4	Waste water / biomass	Sunlight or low power	Very slow rates, low yield
AEM Electrolysis	6–7	Pure or slightly salty water	Electricity	Membrane lifetime still improving
Direct Seawater Electrolysis	4–5	Seawater	Electricity	Corrosion from salt
Waste-to-Hydrogen	5–6	Plastic/tyres /MSW	Heat or electricity	Impurities in waste feedstock

Table 4.2 Biggest Current Problems Matrix

Technology	Feedstock	Biggest Current Problem
Alkaline Electrolyzers	Water (electrolysis)	Maintenance and durability
PEM Electrolyzers	Purified water	Thermal (heat management) issues
Solid Oxide Electrolyzers	Steam (high-temperature water)	Operational challenges
Photoelectrochemical Cells	Sunlight and water	Purity and efficiency
Microbial Electrolysis Cells	Organic waste	Integration and scaling
High-Temperature Electrolysis	Steam and heat energy	Energy supply and system connection

Activity:

Group Activity (30–40 minutes) – “Readiness vs. Impact” Chart

In groups of 4, draw a simple 2×2 grid on flip-chart paper:

- *X-axis: Readiness (Low TRL → High TRL)*
- *Y-axis: Future Impact (Low → High)*

Place the six emerging technologies on the grid using sticky notes.

Discuss and present: Which one should West African countries invest in first for long-term technician jobs? Why?

4.7. Chapter Summary

Emerging hydrogen technologies are currently at Technology Readiness Levels (TRL) 3 to 7, which means they show strong potential but are not yet fully commercial. One example is methane pyrolysis, which produces solid carbon instead of carbon dioxide, making it a cleaner option often called turquoise hydrogen. Some methods, such as thermochemical cycles, require extremely high temperatures that usually come from solar or nuclear energy sources. Other approaches, including biological methods, seawater electrolysis, and waste-to-hydrogen technologies, avoid the use of fossil fuels and fresh water, making them more sustainable. Among these new options, Anion Exchange Membrane (AEM) electrolysis is the closest to being widely used in commercial applications.

Review Questions

1. What does TRL 9 mean? (Short answer)
2. What is the main advantage of methane pyrolysis compared with normal SMR?
3. Why do thermochemical water-splitting cycles need temperatures above 800 °C?
4. Which emerging technology is closest to commercial deployment today?
(a) Biological (b) AEM electrolysis (c) Direct seawater electrolysis
5. Name one emerging method that can use seawater or waste and does not need fresh water.

(Answers: 1. Fully proven commercial technology; 2. Produces solid carbon instead of CO₂; 3. To drive the chemical reactions without electricity; 4. b; 5. Direct seawater electrolysis or waste-to-hydrogen.)

H2-B4: Hydrogen Storage, Transport and Distribution Basics

Learning Objectives:

- Identify hydrogen storage methods
- Describe transport and distribution systems
- Recognize associated safety considerations

H2-B4-1

Compressed, Liquid, and Material-Based Storage

1.1.Importance of Hydrogen Storage

Hydrogen storage means *keeping hydrogen safely until it is needed for use*. Hydrogen is produced at one place (for example, using solar energy), but it is often used somewhere else or at a different time. Hydrogen cannot always be used immediately after production. Storage helps to save energy for later use, transport hydrogen from one place to another, and ensure a continuous energy supply even when production stops, such as at night when solar energy is not available. Figure 4.1 illustrates H₂ production, storage, utilization and environmental impacts.

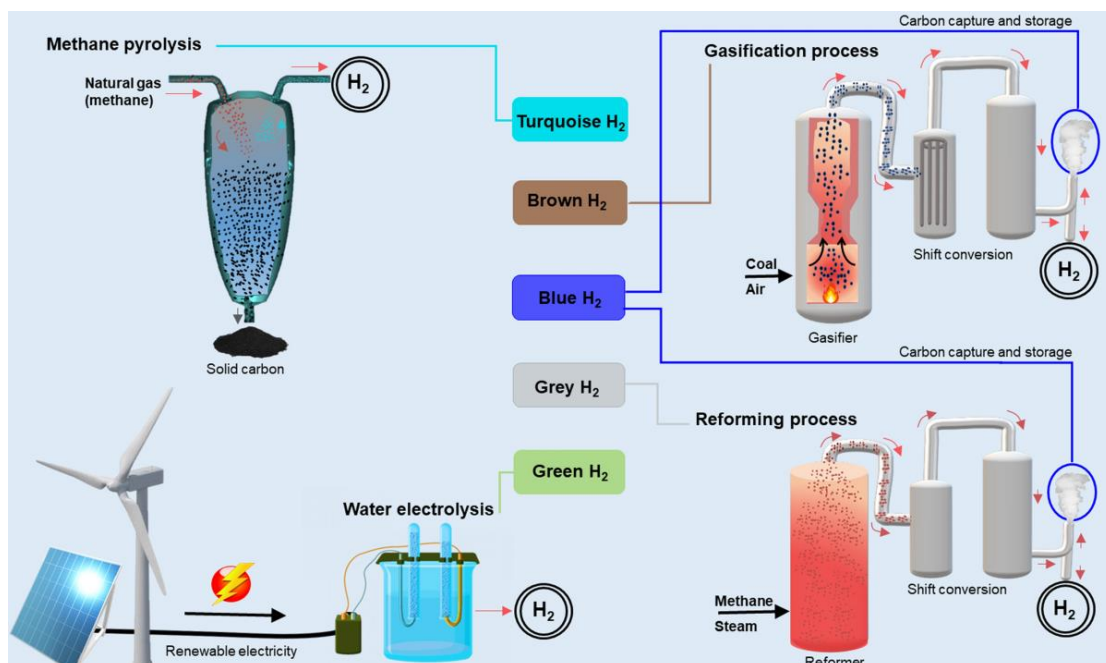


Figure 1.1 Overall process of H₂ production to utilization

In many West African countries, electricity supply can be unreliable, and people often depend on diesel generators, which are expensive and polluting. At the same time, solar energy is

abundant but only available during the day. Hydrogen storage can help store solar energy during the day and provide power at night or during outages. This reduces reliance on diesel fuel and supports cleaner energy use.

For example, a solar-powered hydrogen system in a village works as follows: solar panels produce electricity during the day, this electricity is used to produce hydrogen, the hydrogen is stored, and then the stored hydrogen is used at night for lighting or cooking. The flow diagram in Figure 1.2 shows the production, storage and usage of Green H₂:

Solar/wind production → Hydrogen storage → Usage (vehicle, home, industry)

1. *Solar/Wind Production:* Solar panels and wind turbines generate renewable electricity.
2. *Hydrogen Production:* The electricity powers an electrolyzer that splits water (H₂O) into hydrogen (H₂) and oxygen (O₂). This is called green hydrogen because it has near-zero carbon emissions
3. *Hydrogen Storage:* The produced H₂ is stored in various forms:
 - High-pressure compressed gas tanks
 - Liquefied hydrogen (cryogenic)
 - Underground salt caverns (for large-scale/long-term)
 - Chemical carriers (e.g., ammonia or LOHC)
4. *Usage:*
 - *Vehicles:* Fuel cell electric vehicles (FCEVs) convert H₂ back to electricity to power motors.
 - *Home:* Used for heating, cooking, or electricity via fuel cells.
 - *Industry:* Heavy industry uses it as a clean fuel or feedstock (e.g., steelmaking without coal, ammonia production, chemical processes).

This system enables long-term energy storage and decarbonization of hard-to-electrify sectors.

1.2.Compressed Hydrogen Storage

Hydrogen gas is stored by compressing it into strong tanks at high pressure. It is pushed into a cylinder and compressed so that it occupies less space. It is then stored under very high pressure, typically between 350 and 700 bar. In this method, hydrogen is stored as a gas and requires strong, specially designed cylinders. It is one of the most common and widely used storage methods. Figure 4.3 shows a diagram of a high-pressure cylinder with its valve, pressure gauge and thick tank walls for compressed H₂ storage.

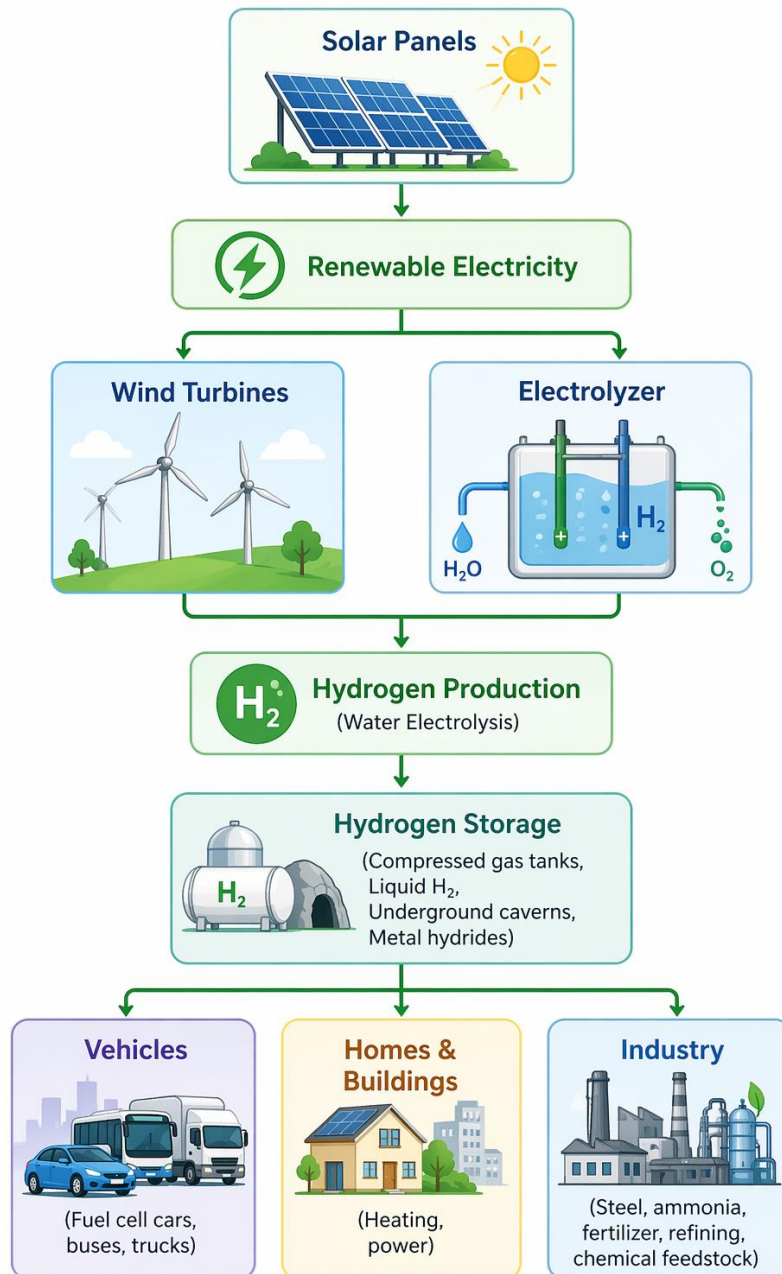


Figure 1.2 Green H₂ production, storage and usage flow diagram

Compressed hydrogen storage is used in hydrogen vehicles such as cars and buses, in industrial gas storage, and in small-scale energy systems.

Advantages: This method uses relatively simple technology and is easy to transport using cylinders. It is suitable for small and medium-scale applications.

Challenges: The high pressure requires strong and sometimes expensive materials. There is also a risk of leaks if the system is not properly handled, and the gas takes up more space compared to liquid storage.

Safety Considerations: Cylinders must be properly sealed and regularly checked. They should be protected from physical damage and stored in well-ventilated areas. It is also important to keep them away from fire and high heat.

Example: In countries like Nigeria or Ghana, hydrogen cylinders could in the future replace LPG cylinders. These cylinders can be transported by trucks to areas where pipelines are not available.

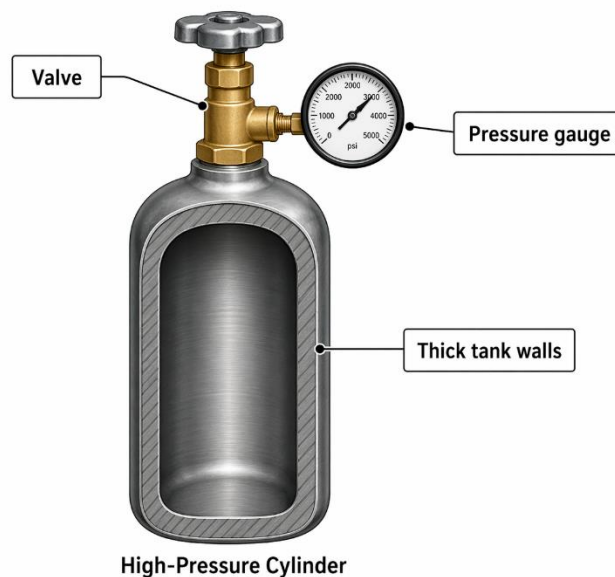


Figure 1.3 High pressure-cylinder with all its parts

1.3. Liquid Hydrogen Storage

Hydrogen is cooled to very low temperatures (-253°C) until it becomes a liquid. Hydrogen gas is cooled down until it changes into a liquid form. It is then stored in special tanks called *cryogenic tanks*, which are designed to maintain extremely low temperatures. Figure 4.4 depicts cryogenic tank showing inner tank (liquid hydrogen), insulation layers and outer protective shell. In this method, hydrogen is stored as a liquid, which allows it to take up much less space than gas. However, it requires very low temperatures to remain in liquid form.

Liquid hydrogen storage is mainly used for large-scale storage, long-distance transport, and industrial or research applications.

Advantages: This method allows a large amount of hydrogen to be stored in a smaller space, making it efficient for large-scale use.

Challenges: It requires expensive cooling systems and advanced technology. Some hydrogen may slowly evaporate over time, a process known as boil-off.

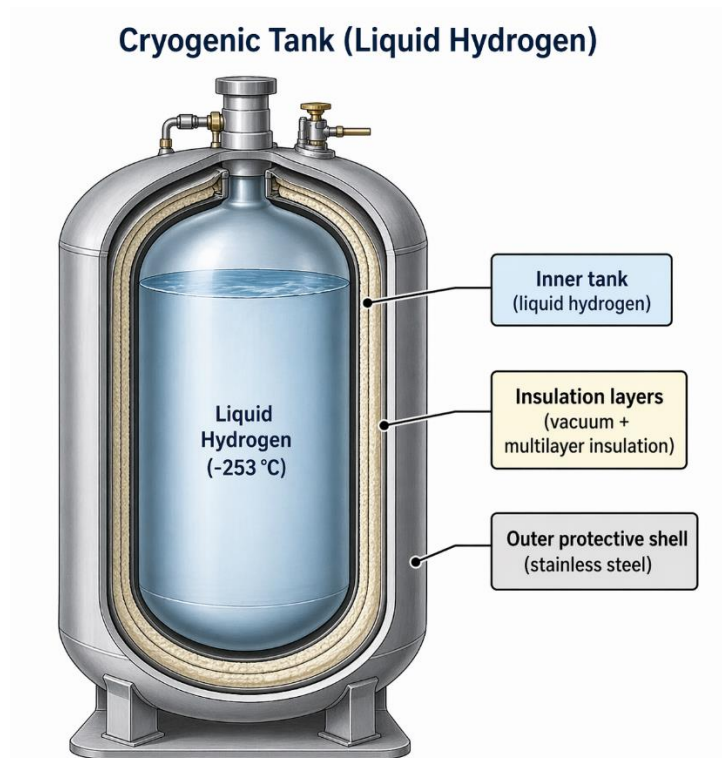


Figure 1.4 Liquid H₂ storage tank (cryogenic tank)

Safety Considerations: Care must be taken to avoid contact with the extremely cold liquid, which can cause injury. Proper insulation is necessary, and pressure must be monitored due to possible evaporation. For example, liquid hydrogen may be used in large energy projects in coastal countries such as Senegal or Côte d'Ivoire, especially for future hydrogen export.

1.4. Material-Based Storage (Solid Storage)

Hydrogen is stored inside solid materials instead of them as a gas or liquid. It is absorbed into a material such as metal or a chemical compound. The material holds the hydrogen safely, and the hydrogen is released when needed. Examples of common materials used include metal hydrides, chemical carriers, and porous materials designed to hold hydrogen. In this method, hydrogen is stored in solid form at lower pressure compared to gas storage. This makes handling safer and easier.

Advantages: Material-based storage is generally safer than high-pressure gas storage, is more compact, and has a lower risk of leakage.

Challenges: This technology is still under development, can be expensive, and may require heat or special conditions to release the stored hydrogen.

Safety Considerations: Proper temperature control is important, and materials must be handled carefully to avoid contamination or damage.

In West Africa, this method could be useful in the future for household energy systems, especially in rural areas where simple and safe solutions are needed.

1.5. Comparison of Storage Methods

Storage methods are selected based on factors such as cost, safety, size, and the intended application. As shown in Table 1.1, compressed gas storage is simple and widely used, liquid hydrogen offers high storage capacity but is more complex, and material-based storage is safer but still under development. Each method also presents specific risks: compressed gas involves high-pressure hazards, liquid hydrogen requires handling extremely low temperatures, and material-based storage, while generally safer, still demands proper handling.

The choice of storage method depends on the availability of technology, cost of equipment, level of safety awareness, and existing infrastructure. For example, rural areas may benefit more from compressed or material-based storage, while industrial zones may use liquid hydrogen systems.

Table 1.1 Comparison various storage methods

Storage Type	Form	Pressure/Temperature	Best Use
Compressed Gas	Gas	High pressure	Vehicles, small systems
Liquid Hydrogen	Liquid	Very low temperature	Large-scale storage
Material-Based	Solid	Low pressure	Safe, future applications

1.6. Chapter Summary

In this chapter, you learned that hydrogen must be stored safely so it can be used when and where it is needed. Storage plays an important role in ensuring a reliable energy supply, especially in regions like West Africa where electricity can be unstable and solar energy is abundant but not always available. You explored three main storage methods: compressed gas, liquid hydrogen, and material-based storage. Each method has its own working principle, advantages, challenges, and safety considerations. Compressed storage is simple and widely used, liquid storage allows high capacity but requires very low temperatures, and material-based storage offers safer handling but is still developing. Understanding these storage methods

helps in choosing the right solution based on local needs, cost, safety, and available infrastructure.

End of Chapter Review Questions

1. What is hydrogen storage and why is it important?
2. Name the three main methods of hydrogen storage.
3. At what condition is hydrogen stored in compressed form?
4. What temperature is required to store hydrogen as a liquid?
5. What is material-based hydrogen storage?
6. Why is hydrogen storage important for solar energy systems in West Africa?
7. Give one advantage and one challenge of compressed hydrogen storage.
8. Explain why liquid hydrogen storage requires special tanks.
9. How does material-based storage improve safety compared to gas storage?
10. Which storage method would be most suitable for rural areas and why?
11. What are two safety precautions when handling compressed hydrogen cylinders?
12. Why can liquid hydrogen be dangerous to handle?
13. What should be done to prevent hydrogen leaks?
14. Compare compressed and liquid hydrogen storage in terms of cost and complexity.
15. In your community, which hydrogen storage method would be most practical? Explain your answer.

H2-B4-2

Hydrogen Supply Chain Overview

2.1. What is a Hydrogen Supply Chain?

A hydrogen supply chain refers to the entire process of producing, storing, transporting, and using hydrogen. It shows how hydrogen moves from where it is made to where it is finally used. It includes several connected steps, as shown in Figure 1.1. First, hydrogen is produced using different energy sources. Next, it is stored safely until needed. After that, it is transported using pipelines, trucks, or ships. Finally, it is delivered to end users such as vehicles, industries, or homes.

A well-organized supply chain ensures that hydrogen is available when and where it is needed. It helps reduce energy shortages, improves efficiency, and supports the use of clean energy. In West Africa, energy systems are often fragmented, and many areas lack reliable electricity. A strong hydrogen supply chain can help connect energy production (such as solar farms in rural areas) to users in cities and industries. It can also reduce dependence on imported fuels like diesel.

2.2. Hydrogen Production Sources

Hydrogen can be produced from different energy sources. The choice of source affects cost, environmental impact, and availability. Hydrogen can be produced using renewable energy such as solar and wind power. In this process, electricity is used to split water into hydrogen and oxygen. This is called electrolysis and produces clean or “green hydrogen.” Hydrogen can also be produced from natural gas or other fossil fuels. This method is currently common but produces carbon emissions unless carbon capture technology is used. Moreover, agricultural waste such as cassava peels, rice husks, and other organic materials can be used to produce hydrogen. This method helps reduce waste and pollution while creating useful energy.

West Africa has strong solar energy potential, making it suitable for green hydrogen production. At the same time, agricultural waste is widely available, offering opportunities for bio-hydrogen production in rural areas. Figure 2.2 illustrates various hydrogen production sources, such as solar panels, wind turbines, natural gas plant and biomass/agricultural waste.

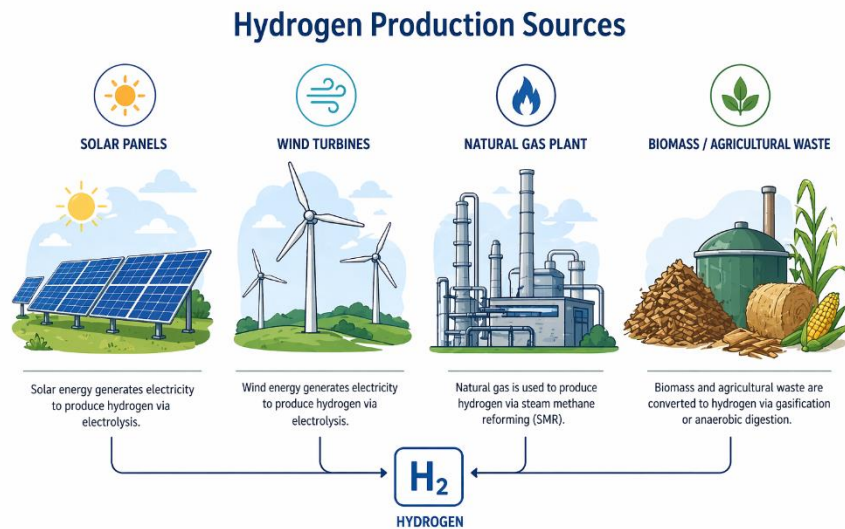


Figure 2.2 Various hydrogen production sources

2.3. Storage and Distribution Stages

Role of Storage in the Supply Chain

Storage: There is a role of storage in the supply chain. i.e., after hydrogen is produced, it must be stored safely before it is transported or used. Storage ensures that energy is available even when production is not continuous.

Distribution of Hydrogen: Distribution involves moving hydrogen from storage locations to users. This can be done through pipelines, trucks, or other transport systems.

Types of Distribution Systems

Hydrogen can be distributed locally (within a community) or over long distances (between regions or countries). The method used depends on the amount of hydrogen and the distance to be covered. In many parts of West Africa, infrastructure is still developing. Hydrogen distribution may initially rely on trucks carrying cylinders, especially in rural areas. In the future, pipelines may be developed in urban and industrial regions. Figure 2.1 shows a map-style diagram showing production site, storage facility, transport routes and end users.



Figure 2.1 Overall diagram of H₂ production site, storage facilities, transport routes and users

2.4. Transport Methods in the Supply Chain

Hydrogen can be transported in different ways depending on distance, quantity, and cost.

- Pipeline Transport:** Pipelines are used to transport hydrogen over long distances. They are efficient for continuous supply but require high initial investment.
- Road Transport (Trucks):** Hydrogen can be transported in cylinders or liquid tanks using trucks. This method is flexible and suitable for areas without pipelines.
- Marine Transport (Ships):** Ships can carry large amounts of liquid hydrogen or hydrogen-based fuels between countries, especially for export and import.

Advantages and Challenges

Each transport method has benefits and limitations. Pipelines are efficient but expensive to build, trucks are flexible but limited in capacity, and ships are suitable for large-scale transport but require advanced infrastructure.

Currently, road transport is the most practical option in many West African countries due to limited pipeline infrastructure. In the future, coastal countries may use ships for hydrogen export.

2.5. End Users of Hydrogen

Hydrogen can be used in different sectors, including transportation, industry, and households.

- **Transport Sector:** Hydrogen can power vehicles such as cars, buses, and trucks using fuel cells. These vehicles produce only water as a byproduct.
- **Industrial Use:** Industries can use hydrogen for processes such as steel production, fertilizer manufacturing, and energy generation.
- **Household and Community Use:** Hydrogen can be used for cooking, lighting, and electricity generation in homes and communities, especially in off-grid areas.

In West Africa, hydrogen can support:

- Clean transport systems in cities
- Industrial development
- Rural electrification where grid power is limited

2.5. Chapter Summary

In this chapter, you learned that the hydrogen supply chain includes all the steps from production to final use. Hydrogen is produced using different sources such as solar energy, natural gas, and biomass, each with its own benefits and challenges. After production, hydrogen must be stored and then distributed through systems like pipelines, trucks, or ships. The choice of transport method depends on cost, distance, and available infrastructure. Finally, hydrogen is used in various sectors including transport, industry, and households. In West Africa, developing a strong hydrogen supply chain can improve energy access, reduce dependence on diesel, and support clean and sustainable development.

End of Chapter Review Questions

1. What is a hydrogen supply chain?
2. List the main stages of the hydrogen supply chain.
3. Name two renewable sources used to produce hydrogen.
4. What is electrolysis?
5. Name three methods used to transport hydrogen.
6. Why is storage important in the hydrogen supply chain?

7. Explain one advantage of using solar energy for hydrogen production in West Africa.
8. Why are trucks commonly used for hydrogen transport in developing regions?
9. Describe how hydrogen can be used in households.
10. What challenges might affect hydrogen distribution in rural areas?
11. Why is it important to handle hydrogen carefully during transport?
12. What could happen if hydrogen leaks during transport or storage?
13. Why should hydrogen transport systems be regularly checked?
14. Compare pipeline and truck transport for hydrogen in terms of cost and flexibility.
15. How can hydrogen supply chains help reduce the use of diesel generators in your community?

H2-B4-3

Pipelines, Cylinders, and Refueling Systems

3.1. Hydrogen Pipelines

Hydrogen pipelines are pipes used to transport hydrogen gas over long distances from production sites to storage facilities or end users. Hydrogen gas is pushed through pipelines using compressors. These pipelines are usually buried underground to protect them from damage and environmental conditions. Pipelines provide a continuous and efficient way to transport large amounts of hydrogen. They are designed using special materials to prevent leaks and handle hydrogen safely.

Advantages: Pipelines are efficient for transporting hydrogen over long distances and can deliver a steady supply. Once installed, they can operate continuously with relatively low operating costs.

Challenges: Building pipelines requires high initial investment and careful planning. Hydrogen can also affect some materials, so special pipeline materials are needed.

Safety Considerations

Pipelines must be regularly inspected for leaks or damage. Monitoring systems are used to detect pressure changes and ensure safe operation.

In West Africa, hydrogen pipelines are still limited, but they may be developed in the future, especially in industrial areas or between major cities where hydrogen demand is high.

3.2. Hydrogen Cylinders and Storage Tanks

Hydrogen cylinders and tanks are containers used to store and transport hydrogen gas or liquid hydrogen.

Types of Cylinders and Tanks

There are small portable cylinders used for local transport and large tanks used for industrial storage. Some tanks store compressed gas, while others store liquid hydrogen. Hydrogen is filled into the cylinders or tanks under controlled conditions. The containers are sealed tightly to prevent leaks and are designed to withstand high pressure or very low temperatures.

Advantages: Cylinders and tanks are flexible and can be easily transported to different locations. They are useful where pipelines are not available.

Challenges: They have limited storage capacity compared to pipelines and may require frequent refilling. Handling and transport must be done carefully.

Safety Considerations: Cylinders should be handled with care, kept upright, and stored in ventilated areas. Regular inspection is necessary to prevent leaks or damage.

In many West African countries, cylinders are already used for LPG. Similar systems could be adapted for hydrogen distribution, especially in rural and peri-urban areas.

3.3. Transport by Road and Sea

Road Transport of Hydrogen

Hydrogen can be transported by trucks carrying cylinders or liquid hydrogen tanks. This method is flexible and suitable for areas without pipelines.

Sea Transport of Hydrogen

Ships are used to transport large quantities of hydrogen, especially in liquid form, between countries or regions.

Hydrogen is loaded into secure containers, transported to the destination, and then unloaded for storage or use.

Advantages: Road transport is flexible and can reach remote areas. Sea transport is efficient for moving large quantities over long distances.

Challenges: Road transport has limited capacity and may require many trips. Sea transport requires specialized ships and infrastructure.

Safety Considerations: Transport vehicles must follow safety standards, including proper labeling, secure fastening of tanks, and regular inspection. Drivers and operators must be trained in handling hydrogen safely.

Road transport is currently the most practical option in many West African countries due to limited infrastructure. Coastal countries such as Ghana and Senegal may use ships for future hydrogen trade.

3.4. Hydrogen Refueling Stations

A hydrogen refueling station is a *facility where hydrogen is supplied to vehicles*, similar to a petrol or diesel filling station.

Main Components of a Refueling Station

A typical station shown in Figure 3.1 includes hydrogen storage tanks, compressors, cooling systems, and dispensing pumps.

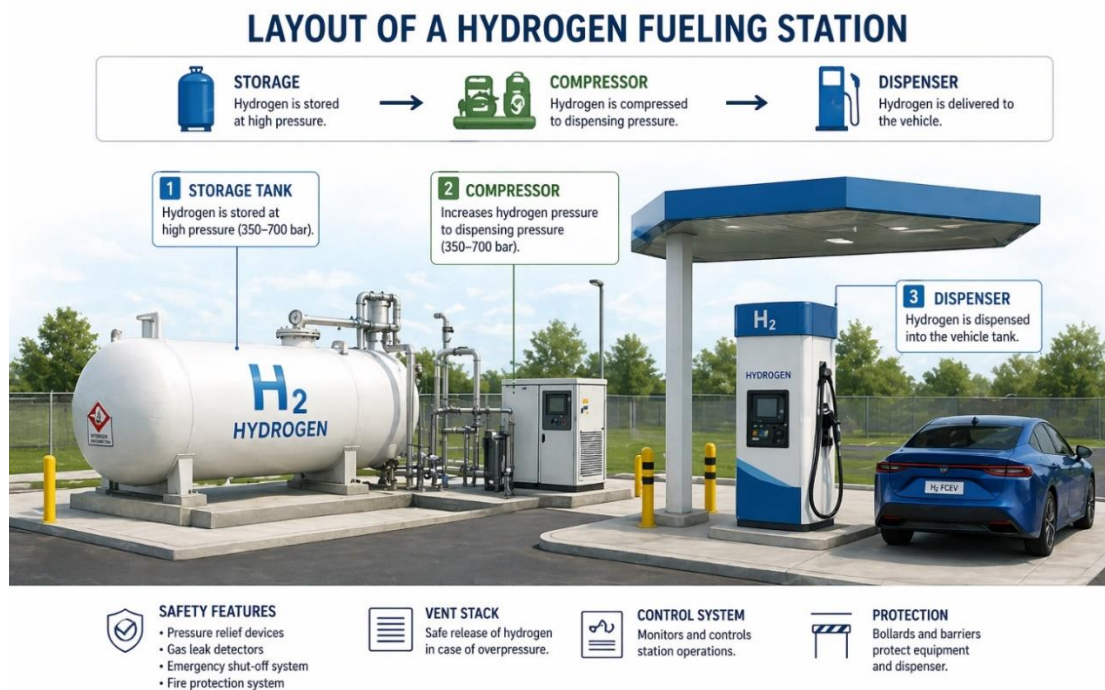


Figure 3.1 Layout of a hydrogen fueling station (storage tank, compressor, dispenser).

How Refueling Stations Work

Hydrogen is stored at the station, compressed to the required pressure, and then delivered into the vehicle's tank through a dispenser.

Advantages: Refueling stations enable the use of hydrogen-powered vehicles and support clean transportation systems.

Challenges: Setting up refueling stations requires investment and infrastructure. There are currently very few such stations in many regions.

Safety Considerations: Stations must be well-designed with safety systems such as leak detectors, ventilation, and emergency shut-off systems.

Hydrogen refueling stations are not yet common in West Africa, but they may be introduced in the future as hydrogen vehicles become more available, especially in major cities.

3.5. Refueling Process for Vehicles

Refueling a hydrogen vehicle involves connecting the vehicle to a dispenser and transferring hydrogen into the tank under high pressure. Step-by-step diagram showing how hydrogen vehicles are refueled. To refuel H₂, first, the vehicle is parked at the station. Then, the nozzle is securely connected to the vehicle tank. Hydrogen is transferred into the tank, and once the tank is full, the nozzle is removed. Hydrogen refueling is quick and usually takes a few minutes, similar to filling a petrol or diesel vehicle.

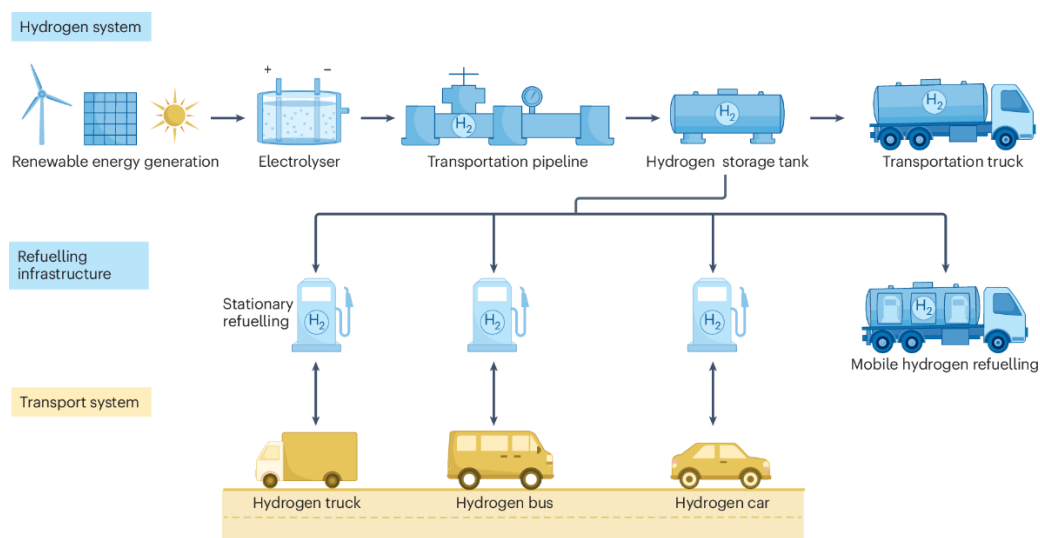


Figure 3.2 Hydrogen refueling process for vehicles

Advantages: The process is fast and convenient, making hydrogen vehicles practical for everyday use.

Safety Considerations: Proper connection of the nozzle is important to prevent leaks. The system automatically controls pressure and stops when the tank is full.

As hydrogen transport develops in West Africa, simple and safe refueling systems will be important for public acceptance and widespread use.

3.6. Chapter Summary

In this chapter, you learned about the main systems used to transport and deliver hydrogen, including pipelines, cylinders, and refueling stations. Pipelines provide an efficient way to move hydrogen over long distances, while cylinders and tanks offer flexible storage and

transport options, especially in areas without pipeline infrastructure. Hydrogen can also be transported by road using trucks or by sea using specialized ships. Refueling stations play a key role in supplying hydrogen to vehicles, making clean transportation possible. Understanding these systems is important for ensuring reliable hydrogen distribution and safe operation, particularly in West Africa where infrastructure is still developing and flexible solutions are needed.

End of Chapter Review Questions

1. What is a hydrogen pipeline?
2. Name two types of hydrogen storage containers.
3. How is hydrogen transported by road?
4. What is a hydrogen refueling station?
5. How long does it typically take to refuel a hydrogen vehicle?
6. Why are pipelines efficient for hydrogen transport?
7. Why are cylinders important in areas without pipelines?
8. Explain one advantage of road transport of hydrogen.
9. What are the main components of a hydrogen refueling station?
10. Why is hydrogen refueling considered convenient?
11. Why must hydrogen cylinders be handled carefully?
12. What safety measures are needed in hydrogen pipelines?
13. Why is proper connection important during vehicle refueling?
14. Compare pipelines and trucks for hydrogen transport in terms of cost and flexibility.
15. What challenges might West Africa face in building hydrogen refueling stations?

H2-B4-4

Basic Infrastructure Requirements

4.1. Hydrogen Infrastructure

Hydrogen infrastructure refers to the *systems and facilities needed to produce, store, transport, and use hydrogen*. It includes everything from production plants to pipelines and refueling stations, such as production facilities, storage systems, transport networks, and end-use applications. All these components must work together for the system to function effectively.

Without proper infrastructure, hydrogen cannot be delivered safely or efficiently. Good infrastructure ensures a reliable energy supply and supports the growth of hydrogen use in different sectors.

In many West African countries, energy infrastructure is still developing. There are challenges such as unreliable electricity supply and limited transport networks. Hydrogen infrastructure can help improve energy access, especially in rural areas, and reduce dependence on diesel generators. Figure 1.1 above depicts overview diagram combining production, storage, transport, and use.

4.2. Production Facilities (Electrolysis Plants)

Production facilities are *places where hydrogen is produced*. One common method is electrolysis, where electricity is used to split water into hydrogen and oxygen. In this method, electricity passes through water in an electrolyzer, breaking it into hydrogen and oxygen gases. When renewable energy sources are used, the hydrogen produced is clean (green hydrogen). An electrolysis plant includes a water supply system, an electrolyzer unit, a power source (such as solar or wind), and gas collection systems.

Advantages: Electrolysis using renewable energy produces clean hydrogen and reduces pollution. It is suitable for regions with abundant sunlight or wind.

Challenges: Electrolysis systems can be expensive to install and require a steady supply of water and electricity.

West Africa has strong solar energy potential, making it ideal for solar-powered electrolysis. Small-scale systems can be used in rural communities to produce hydrogen locally.

4.3. Storage Facilities and Systems

Storage facilities are locations where hydrogen is stored safely before use or transport. These facilities may include tanks, cylinders, or underground storage systems. Figure 4.1 shows hydrogen storage site showing tanks, safety fencing, and monitoring systems. Hydrogen can be stored as compressed gas, liquid hydrogen, or within solid materials, depending on the application and scale. Its storage sites are designed with safety features such as pressure control systems, ventilation, and protective barriers to prevent accidents.

Advantages: Storage facilities ensure that hydrogen is available when needed and help balance supply and demand.

Challenges: Building storage facilities requires careful planning, safety measures, and investment.

Safety Considerations: Storage areas must be well-ventilated and regularly monitored. Safety systems such as pressure relief valves and leak detectors are important.

In West Africa, storage facilities may range from small community-level systems to larger industrial storage sites. Proper design is important to ensure safety and reliability.

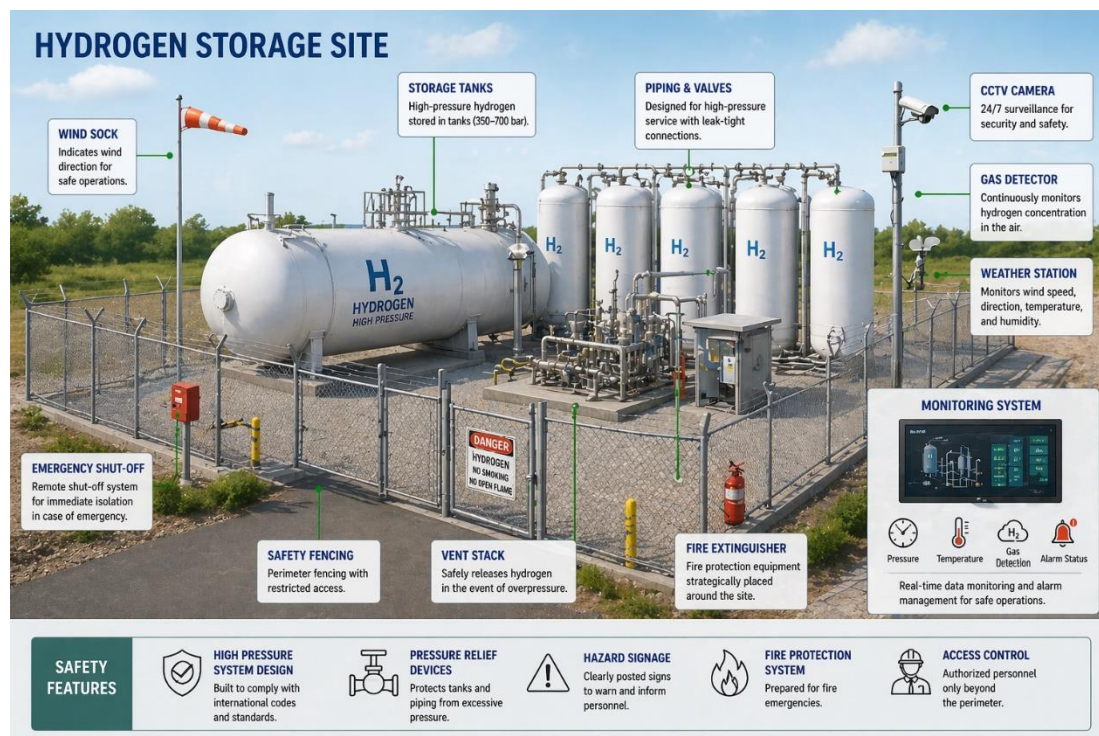


Figure 4.1 Hydrogen storage site showing tanks, safety fencing, and monitoring systems.

4.4. Transport and Distribution Networks

Transport and Distribution networks are systems used to move hydrogen from production sites to storage facilities and end users. Hydrogen can be transported using pipelines, trucks, or ships. Distribution may occur locally or over long distances. Hydrogen is moved through the network and delivered to users such as industries, refueling stations, or homes.

Advantages: Effective transport and distribution networks ensure that hydrogen reaches users efficiently and reliably.

Challenges: Developing these networks requires infrastructure investment and coordination. In some regions, transport systems may be limited.

In many West African countries, road transport is currently the most common method. Over time, pipelines and more advanced systems may be developed in urban and industrial areas.

4.5. Supporting Systems

Supporting systems are additional systems needed to operate hydrogen infrastructure effectively. These include water supply, electricity, and control systems.

- a) **Water Supply:** Water is required for hydrogen production through electrolysis. Clean and reliable water sources are important for efficient operation.
- b) **Power Supply:** Electricity is needed to run electrolyzers and other equipment. Renewable energy sources such as solar and wind are preferred for clean hydrogen production.
- c) **Control and Monitoring Systems:** Control systems are used to monitor pressure, temperature, and flow of hydrogen. These systems help ensure safe and efficient operation.

Advantages: Supporting systems improve efficiency, safety, and reliability of hydrogen infrastructure.

Challenges: Access to clean water and reliable electricity can be a challenge in some areas.

In West Africa, integrating solar power with hydrogen systems can provide reliable energy. Boreholes and rivers may serve as water sources, but water management is important. Diagram showing water supply, electricity input, and monitoring/control units is shown in Figure 4.2.

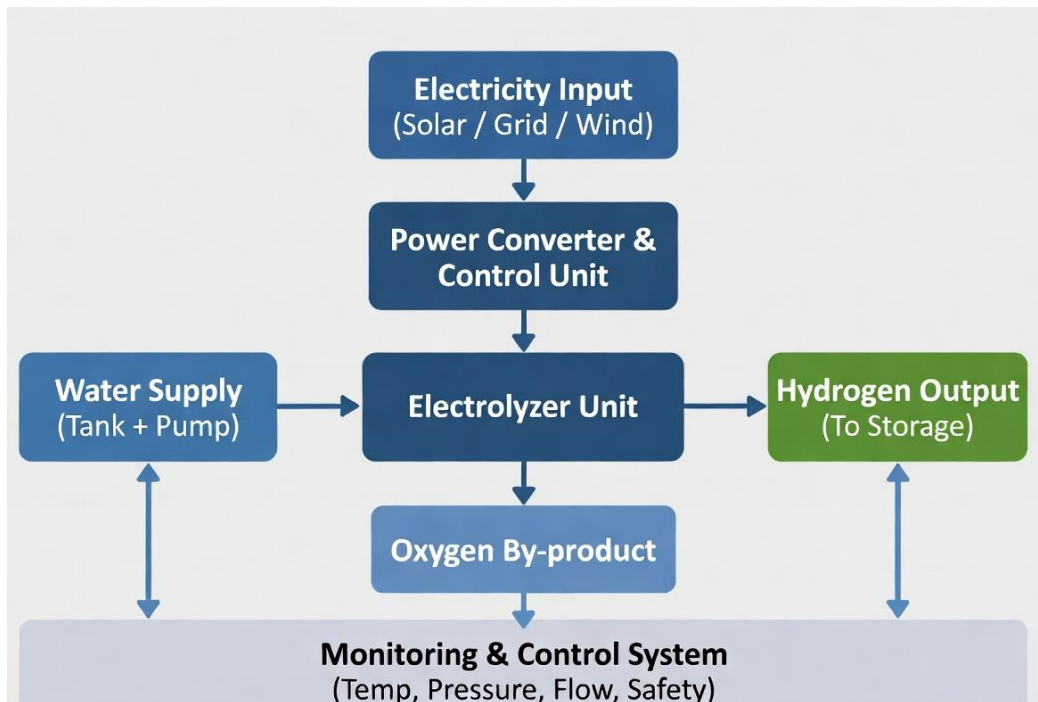


Figure 4.2 Diagram showing water supply, electricity input, and monitoring/control units

4.6. Chapter Summary

In this chapter, you learned that hydrogen infrastructure includes all the systems required to produce, store, transport, and use hydrogen. Production facilities such as electrolysis plants play a key role in generating hydrogen, especially when powered by renewable energy sources like solar and wind. Storage facilities ensure that hydrogen is available when needed, while transport and distribution networks move hydrogen to different users. Supporting systems, including water supply, electricity, and monitoring systems, are essential for safe and efficient operation. In West Africa, developing hydrogen infrastructure can improve energy access, reduce dependence on diesel, and support sustainable development, but it also requires careful planning and investment.

End of Chapter Review Questions

1. What is hydrogen infrastructure? Name two main components of hydrogen infrastructure.
2. What is electrolysis used for? How does electrolysis produce hydrogen?
3. What are storage facilities used for?
4. Name two supporting systems required in hydrogen infrastructure.
6. Why is infrastructure important for hydrogen energy systems?
7. Why are storage facilities necessary in the hydrogen supply chain?

8. What challenges affect hydrogen transport networks?
9. How can solar energy support hydrogen production in West Africa?
11. Why must hydrogen storage facilities be well-ventilated?
12. What role do monitoring systems play in safety?
13. Why is proper water management important in hydrogen production?
14. What infrastructure challenges might rural areas in West Africa face when adopting hydrogen energy?
15. Suggest one way hydrogen infrastructure can reduce diesel generator use in your community.

H2-B4-5

Safety in Storage and Transport

5.1. Importance of Hydrogen Safety

Hydrogen is a useful and clean energy source, but it must be handled carefully to avoid accidents. Like many fuels, hydrogen can be dangerous if not properly managed. It is highly flammable, can be stored under high pressure, and burns with a nearly invisible flame. Figure 5.1 Safety icons showing flammability, high pressure and invisible flame. These characteristics make it important to follow strict safety practices.

Safety ensures that hydrogen can be used without harming people, property, or the environment. Proper safety measures build trust and support wider use of hydrogen technologies.

In West Africa, safety awareness is especially important because hydrogen systems may be new to many users. Training and clear safety guidelines can help prevent accidents and ensure safe adoption, especially in communities already familiar with fuels like LPG and diesel.

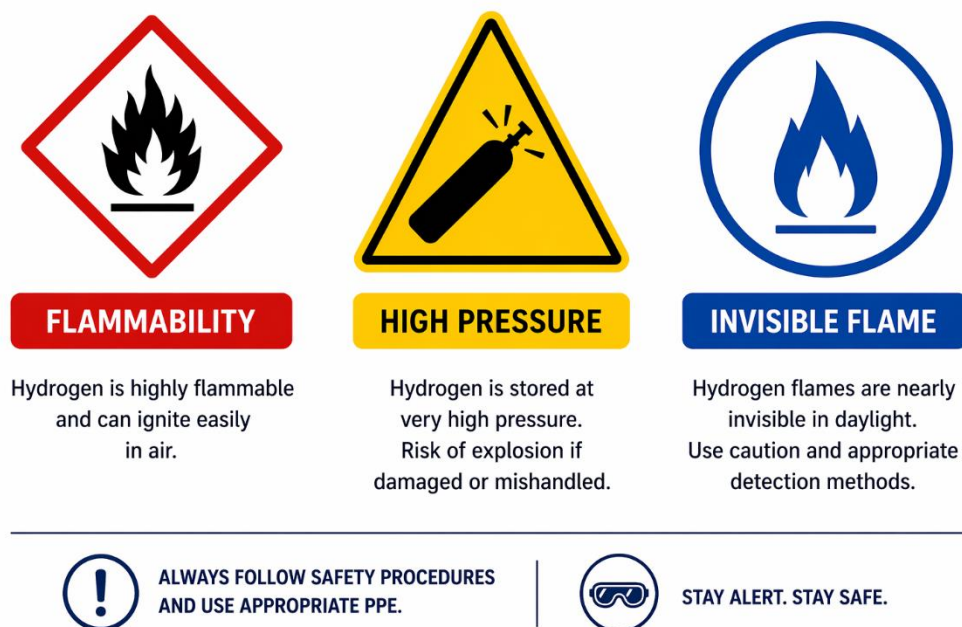


Figure 5.1 Hydrogen safety hazards

5.2. Properties of Hydrogen Related to Safety

Hydrogen has several physical and chemical properties that affect how it behaves and how it should be handled safely.

- *Lightweight Nature:* Hydrogen is the lightest gas and rises quickly in air. This means that in open spaces, it can disperse rapidly, reducing the risk of accumulation.
- *Colorless and Odorless:* Hydrogen cannot be seen or smelled, making leaks difficult to detect without proper sensors.
- *High Flammability:* Hydrogen can ignite easily and burns quickly. It has a wide flammability range, meaning it can catch fire under many conditions.
- *Fast Diffusion:* Hydrogen spreads quickly in the air, which can be both an advantage (reducing buildup) and a risk (spreading leaks quickly).

Understanding these properties is important, especially where detection equipment and safety systems may be limited.

5.3. Safe Storage Practices

- **Proper Storage Conditions:** Hydrogen should be stored in strong, well-designed containers that can handle high pressure or very low temperatures, depending on the storage method.
- **Ventilation:** Storage areas must be well-ventilated to allow any leaked hydrogen to escape safely into the air.
- **Use of Safety Devices:** Safety devices such as pressure relief valves, leak detectors, and monitoring systems are essential to prevent accidents.
- **Handling and Maintenance:** Regular inspection and maintenance of storage systems are necessary to ensure safe operation. Damaged or faulty equipment must be repaired or replaced immediately.

In West Africa, simple and clear storage practices are important, especially in rural areas. Community awareness and proper training can reduce risks. Figure 4.3 shows a diagram showing Proper Hydrogen Cylinder Storage Setup showing, ventilation openings, pressure relief valve, warning signs.

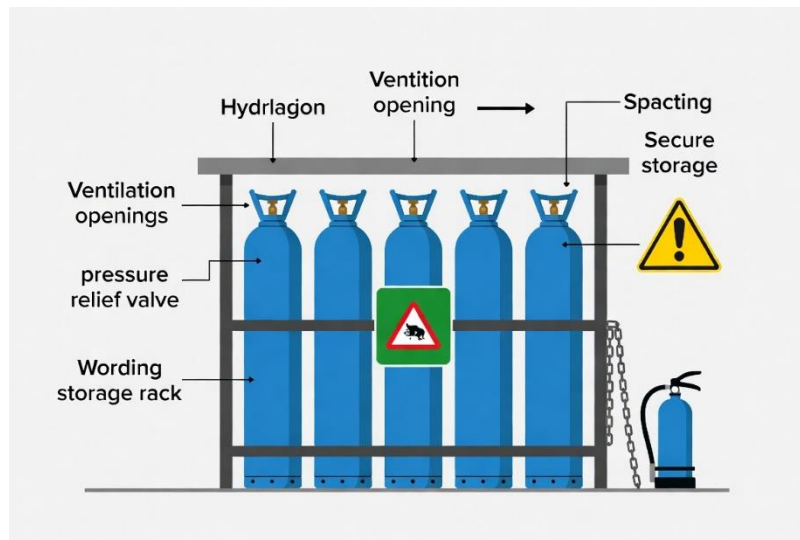


Figure 4.3 Proper Hydrogen Cylinder Storage Setup.

5.4. Safe Transport Practices

- **Safe Handling During Transport:** Hydrogen must be transported in secure containers that are properly sealed and protected from damage.
- **Vehicle Safety Requirements:** Transport vehicles should be clearly labeled and equipped with safety equipment. Tanks must be firmly secured to prevent movement during transport.
- **Training of Personnel:** Drivers and handlers must be trained in safe transport practices and know how to respond to emergencies.
- **Inspection and Monitoring:** Transport systems should be checked regularly for leaks, pressure changes, and structural integrity.

Since road transport is common in West Africa, ensuring that drivers and transport workers understand hydrogen safety is very important for preventing accidents.

5.5. Emergency Response and Risk Awareness

- **Recognizing Emergencies:** Hydrogen emergencies may include leaks, fires, or equipment failure. Early detection is critical to prevent serious incidents.
- **Emergency Response Actions:** In case of a leak or fire, the area should be evacuated immediately. Emergency systems such as alarms and automatic shut-off valves should be activated.
- **Use of Detection Systems:** Hydrogen sensors and alarms help detect leaks quickly and warn people before the situation becomes dangerous.

- **Preparedness and Training:** Workers and communities should be trained on emergency procedures, including evacuation plans and safe response actions.

Emergency response systems may be limited in some areas, so basic training and awareness are essential. Communities should know simple safety steps to protect themselves.

5.6. Chapter Summary

In this chapter, you learned that safety is a critical part of hydrogen storage and transport. Hydrogen has unique properties such as high flammability, being colorless and odorless, and spreading quickly, which require careful handling. Safe storage practices include proper ventilation, use of strong containers, and regular inspection, while safe transport requires secure handling, trained personnel, and proper labeling. Emergency preparedness is also essential, including the use of detection systems and clear response procedures. In West Africa, where hydrogen systems are still developing, building safety awareness and providing proper training are key to ensuring safe and successful use of hydrogen energy.

End of Chapter Review Questions

1. Why is hydrogen safety important?
2. Name two properties of hydrogen that affect safety.
3. Why is hydrogen difficult to detect without sensors?
4. What is the purpose of ventilation in hydrogen storage?
5. What should be done in case of a hydrogen leak?
6. How does hydrogen's lightweight nature affect safety?
7. Why are pressure relief valves important in storage systems?
8. Explain why trained personnel are important for hydrogen transport.
9. What safety measures should be taken during hydrogen transport?
10. How can communities prepare for hydrogen-related emergencies?
11. Why should hydrogen storage areas be regularly inspected?
12. What role do hydrogen sensors play in safety?
13. Why is it important to clearly label hydrogen transport vehicles?
14. What challenges might affect hydrogen safety awareness in rural areas of West Africa?
15. Suggest ways to improve hydrogen safety practices in your community.

H2-B5: Introduction to Hydrogen Applications

Course Duration: 2.5 hrs

Learning Objectives:

- Explain fuel cell working principles
- Identify major fuel cell types
- Describe hydrogen applications in energy systems

H2-B5-1

Introduction to Hydrogen Applications

1.1. What Hydrogen Is and Why It Is Important in Energy Systems

Hydrogen is the simplest and most abundant element in the universe. It is a gas at normal conditions and does not occur freely in large amounts on Earth; instead, it is found in compounds such as water (H₂O) and hydrocarbons (like natural gas). To use hydrogen as a fuel, it must first be extracted from these compounds.

In energy systems, hydrogen is considered an **energy carrier**, not a primary energy source. This means it stores and transports energy produced from other sources such as solar, wind, or fossil fuels. Hydrogen becomes especially important because it can help solve key energy challenges such as storing renewable energy, reducing pollution, and providing energy in sectors where electricity alone is not enough.

Hydrogen can be used to generate electricity, power vehicles, and support industrial processes. When used in fuel cells, hydrogen produces electricity with water as the only by-product, making it a clean option when produced from renewable energy.

1.2.Key Properties of Hydrogen

Hydrogen has several unique physical and chemical properties that make it useful, but also challenging, as an energy carrier.

- *Lightweight:* Hydrogen is the lightest element. This means it rises quickly in air, which can be a safety advantage in open spaces but makes storage difficult.
- *High Energy Content:* Hydrogen contains a large amount of energy per unit mass. This makes it attractive for transport and industrial uses.

- *Low Density:* Because it is very light, hydrogen takes up a lot of space, requiring compression or liquefaction for storage.
- *Highly Flammable:* Hydrogen burns easily and requires careful handling, proper ventilation, and safety systems.
- *Invisible Flame:* Hydrogen flames are nearly invisible, which can make fire detection more difficult.

These properties mean that special materials, tanks, and safety procedures are needed when working with hydrogen systems.

Brainstorming Questions

- What safety challenges might technicians face when working with hydrogen?
- How does hydrogen storage compare with storing diesel in terms of space and safety?
- Could hydrogen replace diesel generators in your community? Why or why not?
- What types of energy problems (power cuts, fuel costs) could hydrogen help solve locally?

1.3. Overview of the Hydrogen Value Chain

The hydrogen value chain describes the full process from producing hydrogen to using it for energy or industrial purposes. Understanding this chain is important for technicians, as each stage requires different equipment and skills. Figure 5.1 presents H₂ value chain with key Elements such as energy source, hydrogen production, storage system, distribution and end-use sectors.

Stages of the Hydrogen Value Chain:

1. *Production:* Hydrogen is produced from water, natural gas, or other materials using methods such as electrolysis or steam methane reforming.
2. *Storage:* Hydrogen is stored in tanks, cylinders, or underground systems. It is often compressed or liquefied to reduce volume.
3. *Distribution:* Hydrogen is transported using pipelines, trucks, or cylinders to where it is needed.
4. *End Use:* Hydrogen is used in fuel cells for electricity, in vehicles, or in industrial processes.

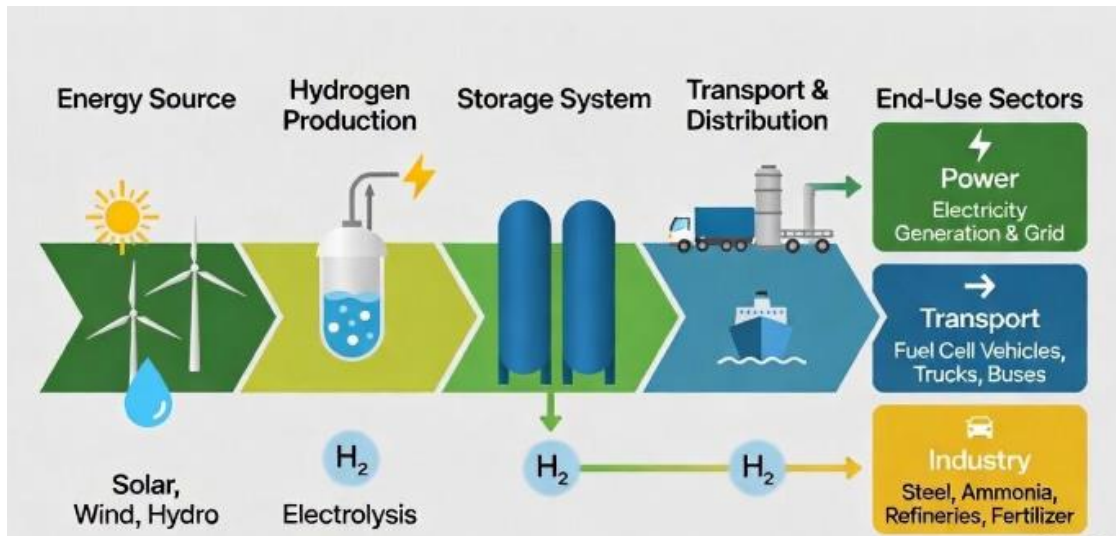


Figure 5.1 Hydrogen Energy Value Chain

1.4. Advantages and Limitations of Hydrogen as an Energy Carrier

Hydrogen offers many benefits, but it also comes with important challenges that must be understood.

Advantages

- *Clean Energy Option:* When produced from renewable sources, hydrogen produces no carbon emissions during use.
- *Energy Storage:* It can store energy for long periods, unlike batteries which discharge over time.
- *Versatility:* Hydrogen can be used in electricity generation, transport, and industry.
- *Supports Renewable Energy:* It helps balance solar and wind power by storing excess energy.

Limitations

- *Storage and Transport Challenges:* Hydrogen requires high-pressure tanks or cooling systems.
- *High Costs:* Production and infrastructure can be expensive, especially for green hydrogen.
- *Safety Concerns:* It is highly flammable and requires strict handling procedures.

- *Limited Infrastructure:* Many regions, including parts of West Africa, lack hydrogen systems and supply networks.

Brainstorming Questions

- How does storing hydrogen compare with storing diesel in your community?
- What are the biggest barriers to using hydrogen locally?
- Which is easier to repair today: a hydrogen system or a diesel generator? Why?

1.5.Chapter Summary

Hydrogen is a versatile energy carrier that can store and deliver energy across multiple sectors. It has a high energy content but poses challenges in storage and transportation due to its low density. The hydrogen value chain includes production, storage, distribution, and end-use. While hydrogen offers clean energy potential, especially when produced from renewable sources, it also requires careful handling and infrastructure development.

End of Chapter Review Questions

1. What is meant by hydrogen as an energy carrier?
2. List two key properties of hydrogen.
3. What are the main stages of the hydrogen value chain?
4. Why is hydrogen difficult to store?
5. State one advantage and one limitation of hydrogen energy.

H2-B5-2

Hydrogen Production and Supply Methods

2.1. Main Hydrogen Production Methods (SMR, Electrolysis, Gasification)

Hydrogen can be produced using different methods depending on available resources, cost, and environmental considerations. The most common methods include:

- **Steam Methane Reforming (SMR):** This is the most widely used method today. It uses natural gas (methane) and steam to produce hydrogen and carbon dioxide (CO₂). It is relatively cheap but produces greenhouse gases.
- **Electrolysis:** This method uses electricity to split water into hydrogen and oxygen. When powered by renewable energy (solar or wind), it produces **green hydrogen**, which is clean and sustainable.
- **Gasification:** In this process, coal or biomass is converted into hydrogen and other gases at high temperatures. Coal-based gasification produces significant emissions, while biomass gasification can be cleaner.

Each method has trade-offs between cost, environmental impact, and technical complexity.

2.2. Renewable vs Non-Renewable Hydrogen Production

Hydrogen production can be classified based on the energy source used:

- **Non-renewable hydrogen:** Produced from fossil fuels such as natural gas and coal. Examples include grey and brown hydrogen. These methods are cheaper but contribute to pollution and climate change.
- **Renewable hydrogen:** Produced using renewable energy sources like solar, wind, or hydropower. Electrolysis powered by renewables produces green hydrogen, which has minimal environmental impact.

The choice between these methods depends on cost, resource availability, and environmental priorities.

Brainstorming Questions

- Which hydrogen production method is most practical in your region today? Why?

- What challenges would technicians face maintaining SMR or electrolysis systems locally?
- Does your region have more access to renewable energy or fossil fuels?
- What would make renewable hydrogen more attractive locally?

2.3. Key Inputs (Water, Electricity, Natural Gas, Coal)

Hydrogen production requires specific inputs depending on the method used:

- **Water:** Essential for electrolysis. Clean water improves efficiency and system life.
- **Electricity:** Needed for electrolysis. The cost and source of electricity greatly affect hydrogen cost.
- **Natural Gas:** Used in SMR. It is widely available in some regions but contributes to emissions.
- **Coal or Biomass:** Used in gasification. Coal is polluting, while biomass can be a cleaner alternative if managed sustainably.

The availability and cost of these inputs strongly influence which production method is most suitable in a given region.

Figure 2.1 shows H₂ production pathways with key elements such as fossil-based production, renewable-based production and inputs and outputs. The processes of the pathways with their inputs and outputs can be represented as

Natural Gas $\longrightarrow$ [SMR] $\longrightarrow$ Hydrogen + CO₂

Coal $\longrightarrow$ [Gasification] $\longrightarrow$ Hydrogen + CO₂

Water + Electricity $\longrightarrow$ [Electrolysis] $\longrightarrow$ Hydrogen + Oxygen

Brainstorming Questions

- What inputs are easily available in your local area?
- How does the cost of electricity affect hydrogen production in your region?

2.4. Basic Hydrogen Supply Infrastructure

Once hydrogen is produced, it must be stored, transported, and delivered safely. This requires specialized infrastructure:

- **Storage Systems:** Hydrogen is stored in high-pressure tanks, cylinders, or underground storage facilities.
- **Transport Systems:** Hydrogen can be transported via pipelines, trucks, or cylinders depending on distance and scale.
- **Distribution Networks:** Infrastructure is needed to deliver hydrogen to users such as industries, fueling stations, or microgrids.
- **Safety Systems:** Includes leak detection, ventilation, and pressure control systems.

Developing infrastructure is one of the biggest challenges for hydrogen adoption, especially in developing regions.

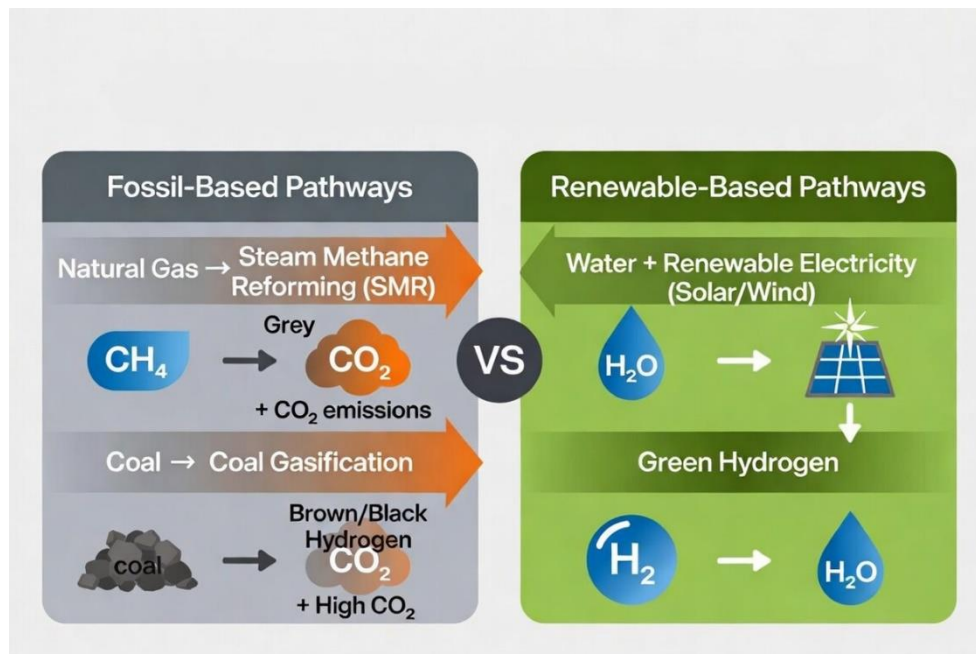


Figure 2.1 Explanatory Diagram of Hydrogen Production Pathways

In areas like Senegal, a coastal wind farm powers an electrolyzer can produce hydrogen. Then the hydrogen can be stored and supplied to a nearby fish processing facility to provide clean energy for refrigeration and operations.

2.5. Chapter Summary

Hydrogen can be produced through several methods, including steam methane reforming, electrolysis, and gasification. These methods differ in cost, environmental impact, and required inputs such as water, electricity, natural gas, or coal. Renewable hydrogen production is cleaner

but currently more expensive in many regions. Developing supply infrastructure—including storage, transport, and distribution systems—is essential for expanding hydrogen use.

End of Chapter Review Questions

1. Name two hydrogen production methods.
2. What inputs are required for electrolysis?
3. What is the difference between renewable and non-renewable hydrogen?
4. Why is infrastructure important in hydrogen supply?
5. What is one disadvantage of fossil-based hydrogen production?

H2-B5-3

Hydrogen in Power Generation, Transport, and Industry

3.1. Hydrogen in Power Generation (Fuel Cells, Turbines)

Hydrogen can be used to generate electricity in two main ways: *fuel cells* and *hydrogen turbines*.

- **Fuel Cells:** These devices convert hydrogen directly into electricity through an electrochemical reaction. They are efficient and produce only water as a by-product. Fuel cells are suitable for small-scale and backup power systems.
- **Hydrogen Turbines:** Hydrogen can be burned in turbines to generate electricity, similar to natural gas turbines. This method is suitable for large-scale power generation.

Hydrogen is especially useful for backup power and for supporting renewable energy systems when solar or wind power is not available.

Brainstorming Questions

- Could hydrogen fuel cells replace generators in your workplace? Why or why not?
- Which system would be easier to maintain locally: a fuel cell or a diesel generator?

3.2. Hydrogen in Transport (Cars, Buses, Trucks)

Hydrogen is used in transportation mainly through *fuel cell vehicles (FCVs)*. These vehicles use hydrogen to produce electricity that powers an electric motor.

- **Applications include:**
 - Cars
 - Buses
 - Trucks
 - Trains (in some regions)

Hydrogen vehicles are quiet, efficient, and produce no harmful emissions. However, they require specialized fueling stations and trained technicians.

Brainstorming Questions

- Would hydrogen vehicles be practical in your area today? Why or why not?
- What challenges might arise in maintaining hydrogen buses compared to diesel buses?

3.3. Hydrogen in Industry

Hydrogen already plays a significant role across multiple industrial sectors and is becoming increasingly important in the transition toward cleaner production processes. In *fertilizer production*, hydrogen is a key raw material used in the synthesis of ammonia through the *Haber–Bosch process*. Ammonia is a fundamental component of nitrogen-based fertilizers, making hydrogen indispensable for global agricultural productivity and food security. In the *oil refining industry*, hydrogen is extensively used in processes such as hydrocracking and hydrotreating, where it helps remove impurities like sulfur, nitrogen, and heavy metals from crude oil, thereby improving fuel quality and ensuring compliance with environmental standards. Additionally, in *steel production*, hydrogen is emerging as a promising alternative to traditional carbon-intensive methods. It can be used as a reducing agent in place of coke or coal during iron ore processing, significantly lowering carbon dioxide emissions. This shift toward hydrogen-based steelmaking represents a crucial step in decarbonizing one of the most energy-intensive and polluting industrial sectors.

These applications are important because they use large amounts of energy and offer opportunities for reducing pollution.

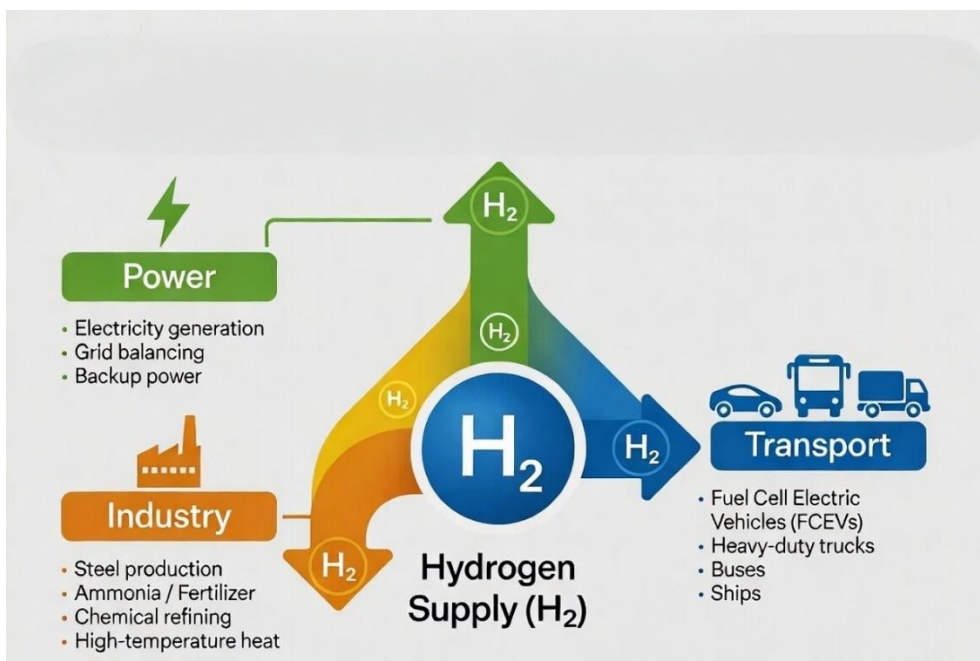


Figure 3.1 Hydrogen Applications Across the three main sectors of use

Brainstorming Questions

- Which industries in your region could benefit from hydrogen use?
- How could hydrogen reduce pollution in local industries?

3.4. Benefits and Limitations Across Sectors

Benefits

- Reduces air pollution and carbon emissions
- Can replace fossil fuels in difficult sectors
- Flexible use across power, transport, and industry

Limitations

- High cost of hydrogen technologies
- Limited infrastructure (fueling stations, pipelines)
- Need for skilled technicians and maintenance systems

Understanding these benefits and limitations helps in deciding where hydrogen can be applied effectively.

Brainstorming Questions

- Which sector (power, transport, or industry) is most suitable for hydrogen in your region?
- What skills would technicians need to support hydrogen systems?

A city in Lagos can introduce hydrogen-powered buses to reduce diesel consumption and improve air quality in urban areas.

3.5. Chapter Summary

Hydrogen can be used across multiple sectors including power generation, transport, and industry. It generates electricity through fuel cells and turbines, powers vehicles, and supports key industrial processes. These applications offer cleaner alternatives to fossil fuels. However,

challenges such as cost, infrastructure, and technical capacity must be addressed for widespread adoption.

End of Chapter Review Questions

1. How is hydrogen used to generate electricity?
2. Name one application of hydrogen in transport.
3. Which industries commonly use hydrogen?
4. What is one advantage of hydrogen in transport?
5. What limits hydrogen adoption across sectors?

H2-B5-4

Hydrogen for Energy Storage and Microgrids

4.1. Role of Hydrogen in Energy Storage

Hydrogen can store energy for long periods, making it useful for balancing energy supply and demand. When excess electricity is available (e.g., from solar panels during the day), it can be used to produce hydrogen through electrolysis. The hydrogen can then be stored and used later to generate electricity.

This makes hydrogen especially valuable in areas with unreliable power supply or high dependence on renewable energy.

Brainstorming Questions

- How could hydrogen help reduce power outages in your community?
- What are the benefits of storing energy instead of using it immediately?

4.2. Comparison with Batteries

Hydrogen storage and batteries both store energy, but they have different strengths:

- **Batteries:**
 - Good for short-term storage
 - Fast response
 - Limited storage capacity
- **Hydrogen:**
 - Suitable for long-term and large-scale storage
 - Can store energy for days or months
 - Requires more complex systems

Choosing between them depends on the application and required storage duration.

Brainstorming Questions

- Would you prefer maintaining batteries or hydrogen systems? Why?

- Which system is easier to repair locally?

4.3. Hydrogen-Based Microgrids

A microgrid is a small, local energy system that can operate independently from the main grid. Hydrogen can be integrated into microgrids to improve reliability. **Figure 4.1 depicts hydrogen storage in a renewable microgrid, with key elements, such as renewable energy source, electrolyzer, hydrogen storage, fuel cell and electricity supply.**

In a hydrogen-based microgrid:

- Renewable energy generates electricity
- Excess energy produces hydrogen
- Hydrogen is stored
- A fuel cell converts hydrogen back to electricity when needed

This setup ensures continuous power even when renewable sources are not available.

Brainstorming Questions

- Could hydrogen microgrids work in rural communities in your region?
- What challenges might arise in maintaining such systems?

4.4. Long-Term and Seasonal Energy Storage

Hydrogen is particularly useful for storing energy over long periods:

- **Long-term storage:** Energy can be stored for days or weeks.
- **Seasonal storage:** Excess energy from one season (e.g., sunny season) can be stored and used in another.

This makes hydrogen important for stabilizing renewable energy systems and ensuring consistent energy supply.

Brainstorming Questions

- How could seasonal energy storage benefit agriculture or businesses locally?
- What infrastructure would be needed to support long-term hydrogen storage?

Figure 4.1 Hydrogen Storage in a Renewable Microgrid

Key Elements:

- Renewable energy source
- Electrolyzer
- Hydrogen storage
- Fuel cell
- Electricity supply

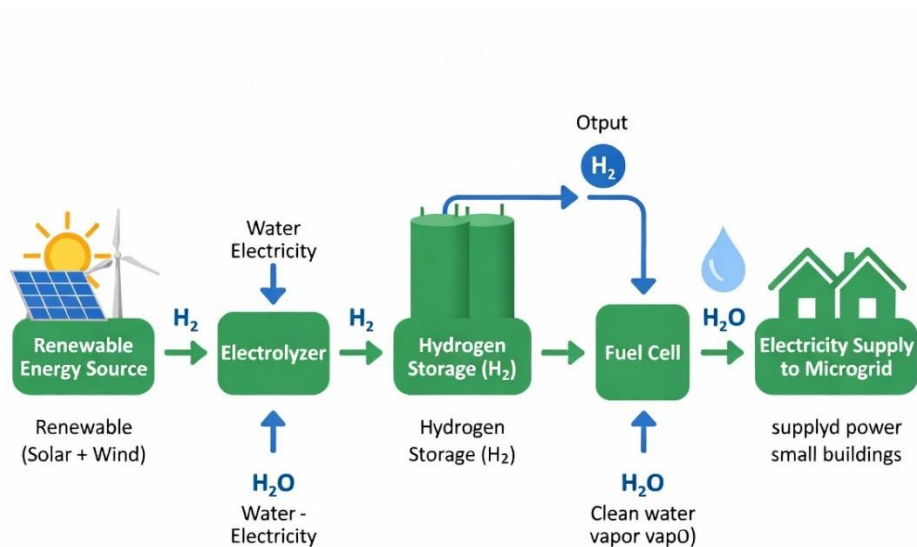


Figure 4.1 Hydrogen Storage in a Renewable Microgrid

A rural community in Mali can install a solar-powered microgrid with hydrogen storage. During the day, solar panels produce electricity and hydrogen. At night, the stored hydrogen can be used to generate electricity for homes and small businesses.

4.5. Chapter Summary

Hydrogen provides an effective solution for storing energy, especially in renewable energy systems. It is suitable for long-term and large-scale storage, unlike batteries which are better for short-term use. Hydrogen can be integrated into microgrids to provide reliable electricity in off-grid areas. This makes it highly valuable for rural and remote communities.

End of Chapter Review Questions

1. Why is hydrogen useful for energy storage?
2. How does hydrogen storage differ from battery storage?
3. What is a microgrid?
4. What role does a fuel cell play in a hydrogen system?
5. Why is hydrogen suitable for long-term storage?