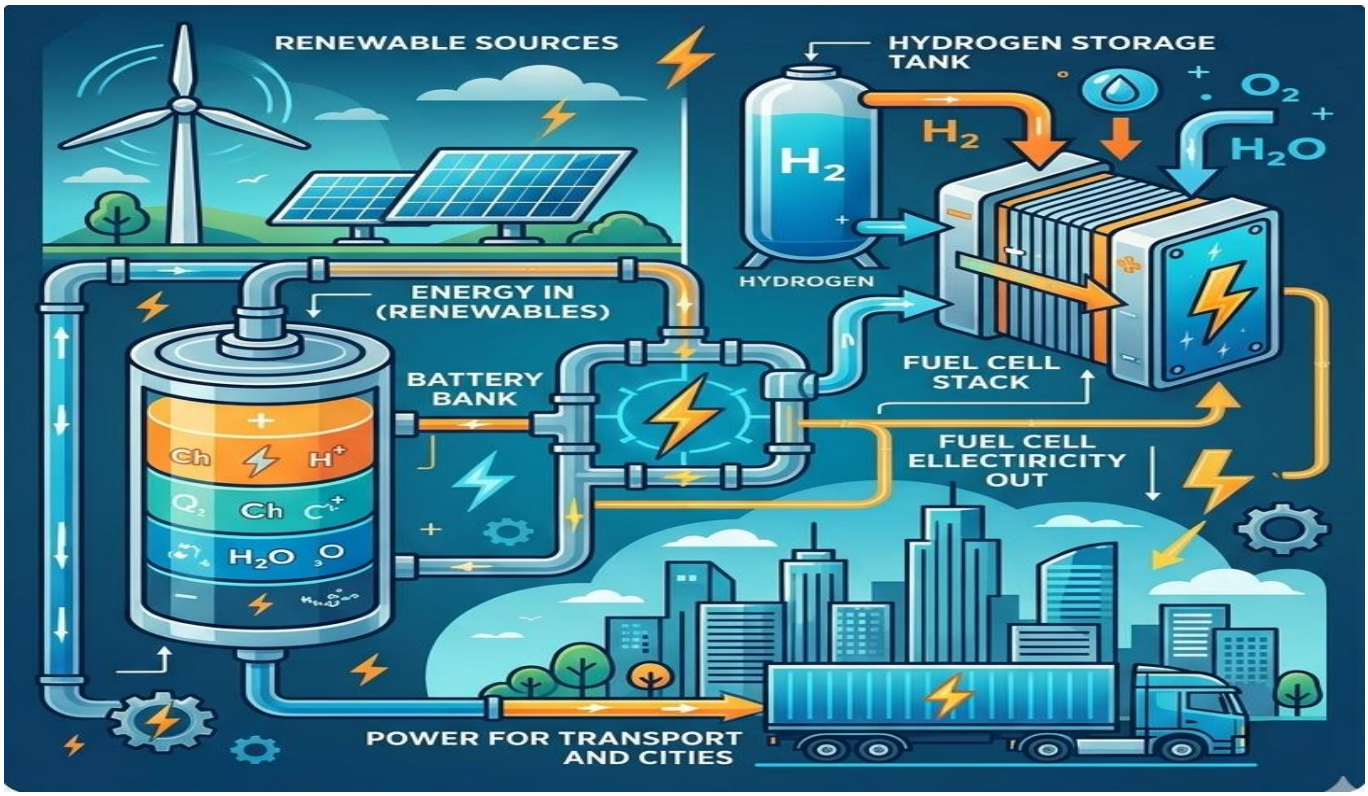
PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
Ministry of Higher Education and Scientifc Research
University of Amar Telidji - Laghouat
Faculty of Technology
Department of Electronics

Lecture Notes

DOMAIN: Science & Technology
FIELD: Renewable Energies
SPECIALTY: Master 2 Renewable Energies

Dr. GUEFFAF Hamza

Energy Storage and Fuel Cells



2025-2026

Foreword

Energy storage involves preserving a specific quantity of energy for subsequent use. By extension, the term also encompasses the storage of energy-bearing matter.

Energy storage lies at the core of contemporary challenges, whether in terms of optimizing energy resources or facilitating access to them. It enables the balancing of energy 'production' and 'consumption' by minimizing losses. Energy that is stored when availability exceeds demand can be redistributed when requirements increase. In response to the intermittency or production fluctuations of certain energy sources, such as renewables, this process also ensures a constant supply to meet demand.

Storage methods depend on the type of energy involved. Fossil energy sources (coal, gas, oil), occurring naturally in the form of reservoirs, inherently function as reserves. Once extracted, they can be easily isolated, stored, and transported from a technical standpoint. However, storage proves more complex for intermittent energies: their production is mediated by energy carriers such as electricity, heat, or hydrogen, which require specific storage systems.

This module is designed for first-semester students in the second year of the Master's degree in Renewable Energy and Electrical Engineering. Its content adheres to the curriculum established by the Ministry of Higher Education and Scientific Research.

The objective of this module is to acquire the fundamental principles of various storage methods and to understand the operational mechanisms of converting H_2 into electricity via Fuel Cells (FC). It also covers the different systems used for electrical energy storage.

Chapter III

Electrochemical Energy Storage

General Introduction

General Introduction

Global energy consumption is set to rise over the coming decades, although predicting and quantifying this increase remains a challenge. The need for short-term pollution reduction, combined with the long-term depletion of fossil fuels—which currently dominate the global energy mix—makes a profound energy transformation inevitable.

To date, renewable energy sources account for only 19% of the total, reaching 27,000 terawatt-hours in 2023. Nevertheless, renewable energy resources are vast and diverse; their annual estimated potential is as follows:

- ✓ **Geothermal energy:** $0{,}025.10^9$ GWh per year
- ✓ **Tidal energy:** $0{,}0005.10^9$ GWh per year
- ✓ **Hydropower:** $0{,}025.10^9$ GWh per year
- ✓ **Biomass energy:** $0{,}058.10^9$ GWh per year
- ✓ **Wind energy:** 1.10^9 GWh per year
- ✓ **Solar energy:** 26.10^9 GWh per year.

However, renewable energy sources are inherently intermittent and geographically dispersed. These characteristics, combined with the distribution of consumption centers, pose significant challenges for energy storage and transport. For instance, how can solar energy in the Sahara be effectively harnessed? Two complementary energy carriers are emerging to enable more flexible exploitation: electricity and hydrogen. While electricity storage remains a major challenge (transportation to a lesser extent), its advantages are undeniable, notably its low environmental impact and high conversion efficiency.

Hydrogen, with an energy density of 30 kWh/kg, offers highly promising prospects for storage and transport. The development of this energy carrier only reaches its full potential when coupled with Fuel Cells (FC), which generate electrical energy by combining hydrogen with oxygen (a highly abundant primary resource). Remarkably, the by-products of this reaction—water and heat—are non-polluting and can even be repurposed.

The storage of renewable energy via hydrogen could thus be achieved during its synthesis: either through the **electrolysis of water** (a highly abundant primary resource) using electrical energy from wind or solar sources, or by transforming **biomass** (via bacteria, etc.). It should be noted that hydrogen does not exist in its natural state on our planet; significant research is still required to master efficient storage at **ambient pressure** (using carbon nanotubes, etc.) as well as at high pressure.

Current solutions for storing electrical energy involve first transforming it into another storable form of energy, then performing the reverse transformation when electricity is needed again. The storable form of the energy can be mechanical, chemical, biological, or thermal. This course will present the various storage modes along with their underlying theories and practical applications.

Chapter One provides a general overview of various storage types, followed by a detailed analysis of mechanical energy storage in both kinetic and potential forms.

Chapter Two focuses on fuel cells (FC), covering their operating principles, kinetics, efficiency, and structural design. Consequently, it presents the various types of fuel cells: AFC, PEMFC, DMFC, SOFC, MCFC, PAFC, and others.

Finally, **Chapter Three** addresses electrochemical energy storage, beginning with an introduction to solar batteries, their properties, specifications, and applications beyond the solar context. Following a brief overview of capacitors, we will examine supercapacitors, including their various categories, characterization and modeling, aging processes, and practical use cases.

CHAPTER I

General Overview of Various Storage Types

I.1 Energy Storage Modes

Energy can be stored in one of the various modes shown in Figure I.1

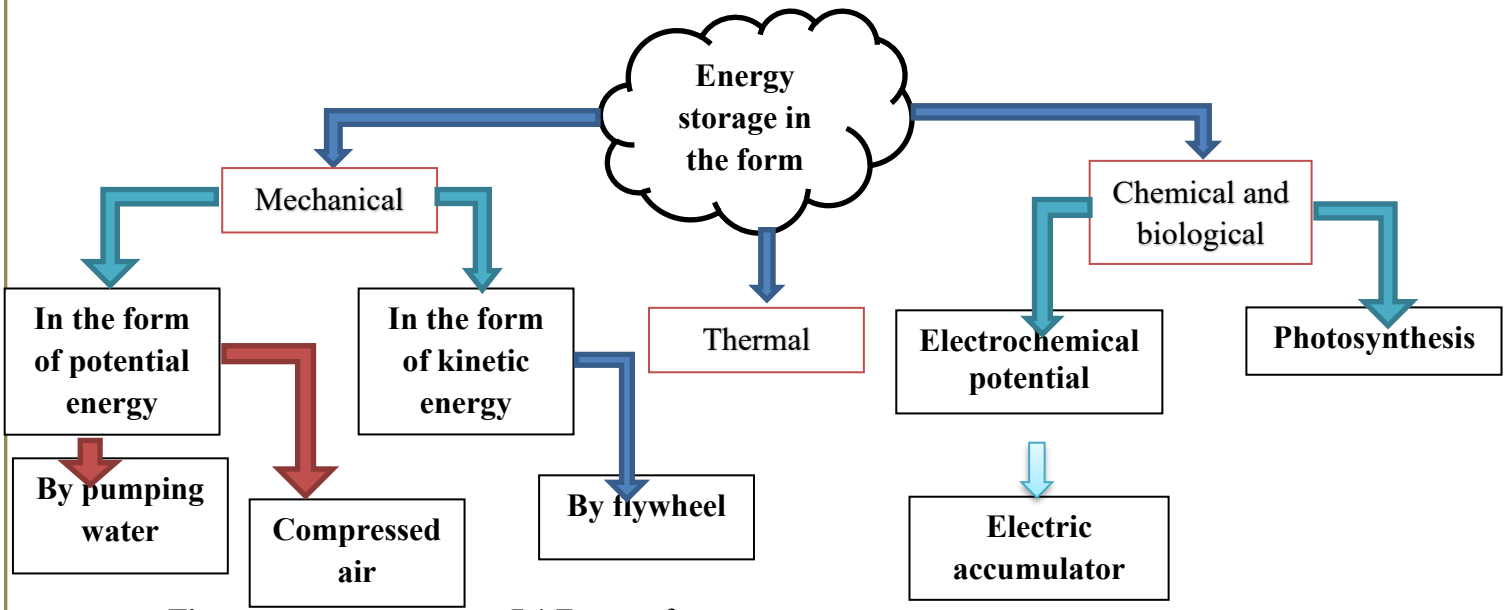


Fig I.1 Forms of energy storage

I.2 Energy Storage Scales

Energy storage types can also be classified according to their storage scale, as shown in Table I.1.

- **Large-scale storage:** These methods are capable of storing energy in vast quantities and can be implemented by a grid operator (TSO/DSO).

- **Small and medium-scale storage:** These applications can benefit not only the electrical system but also distributed generation for various uses.

Table I.1 Energy storage scale

Energy storage scale	
Large-scale storage	**Small and medium-scale storage**
➢ Pumped Hydro Storage (PHS) ➢ Compressed Air Energy Storage (CAES) ➢ Coupling with natural gas or liquefied gas storage ➢ Biological storage ➢ Hydrogen-based storage ➢ Thermal energy storage (TES)	➢ Electrochemical accumulator / Battery ➢ Flywheel energy storage ➢ Inductance, superconductivity ➢ Supercapacitor ➢ Compressed air

I.3 Storage types

I.3.1 Pumped Hydroelectric Storage (PHS)

Pumped energy storage was developed to optimize the operation of large power plants within interconnected grids, addressing time-variable electricity demand (peak hours/off-peak hours). At the beginning of the 21st century, this form of energy storage has experienced a significant new wave of development, driven by the expansion of renewable energy sources.

Pumped storage is the most economical means of utility-scale electricity storage, provided that suitable sites are available: specifically, the ability to develop or utilize an upper reservoir that can be connected via conduits and tunnels to a lower body of water (Fig. I.2). The key components are the turbines and pumps, or reversible pump-turbines that combine both functions.

Fig I.2 View of the two reservoirs at the energy storage station

For greater operational flexibility in both pumping and turbining modes, the latest pump-turbines utilize variable-speed technology. To date, pumped energy storage is the most widely used form of stationary energy storage worldwide. Beyond its primary purpose of 'storing' electricity for use during peak demand, pumped storage provides multiple ancillary services to electrical grids and systems, serving as a critical backup during grid disturbances. It is currently experiencing significant growth to help mitigate the intermittency of solar and wind renewable energy.

I.3.1.1 Principles and Description

The principle of this energy storage method is to pump water from one reservoir to another located at a higher altitude during periods of surplus electricity. Then, when demand exceeds production, the water is released through turbines to generate electrical energy. This process requires two water reservoirs at different elevations (Figure 1), tunnels, pipes, or penstocks connecting the two reservoirs, pumps and turbines, as well as ancillary structures. The energy is stored in the form of gravitational potential energy.

A volume of water **V** at a specific altitude **h** above sea level indeed corresponds to a potential energy:

$$E_P = \rho g V h$$

With:

ρ density of water (mass density),

g acceleration due to gravity (gravitational acceleration).

Between two reservoirs with levels at different altitudes, separated by $\mathbf{H_b}$, known as the gross head, there is a potential energy difference:

$$E_P = \rho g V H_b$$

With:

V the volume of water that can effectively be transferred from one reservoir to the other, and vice-versa.

This volume V depends on the reservoir capacities, given that a specific reservoir is characterized by a minimum operating level (below which operation is prohibited) and a maximum level. Since the water levels of both lakes evolve during a pump-storage cycle, the gross head H_b varies throughout the process. Consequently, the storable energy is more commonly defined by the useful volume of the reservoirs.

Example:

In the new Linthal pumped-storage project in Switzerland, the elevation head between the two reservoirs is expected to range from 560 m to 724 m, depending on their respective filling levels.

I.3.1.2 Global Characteristics of a PHS Plant

A pumped-storage hydropower (PHS) facility can be broadly characterized by the following parameters:

- **Maximum Energy E:** The maximum energy that can be stored as potential energy
- **Installed Pumping Power P_p:** The electrical power capacity dedicated to pumping.
- **Installed Turbining Power P_t** The electrical power capacity dedicated to generation (turbining)
- **Round-trip Efficiency η**, The ratio between the electrical energy consumed during pumping E_p to store energy E and the electrical energy produced during turbining E_t by consuming that potential energyE:

$$\eta = \frac{E_t}{E_p}$$

- **Degree of Flexibility:** The capacity for rapid power adjustment in both pumping and turbining modes.

In existing PHS plants, pumping and turbining capacities are generally of the same order of magnitude—though slightly lower for pumping than for turbining—and typically range from several hundred MW to 3,000 MW for the largest facilities.

The transferable energy E per cycle for the largest facilities exceeds 10 GWh. The round-trip efficiency is typically in the range of 75% to 80% (reaching 80% for the most recent plants). Gross heads (H_b) are most often below 700 or 800 m, which appears to be a technical limit for the utilization of variable-speed pump-turbines.

Efficiency is not an intrinsic characteristic of a facility; it depends on the actual pumping and turbining cycles performed. In particular, it is determined by whether the pumps and turbines are operated within their optimal operating ranges, and thus at their peak efficiency. It is also subject to frictional losses within the conduits and tunnels.Rendement d'un cycle de pompage et turbinage

If we pump a volumetric flow rate Q from altitude h to an altitude $h+H_b$, the gross power P_b required for this elevation is expressed as follows::

$$P_b = \rho g Q H_b$$

In practice, this gross power must be supplemented to compensate for all frictional losses:

- Friction within the conduits supplying water to the turbines (referred to in hydraulics as head losses); the corresponding power is expressed as::

$$P = \rho g Q \delta H_b$$

With :

- δH hydraulic head loss across the circuit, measured in meters of water column (mWC); it is proportional to the square of the water velocity (it may therefore vary throughout the cycle).

- Frictional and energy losses within the pump(s), represented by the pumping efficiency η_p (< 1) of the machine.

The electrical power that must effectively be supplied is therefore:

$$P_b = \rho g \frac{H_b + \delta H}{\eta_p} Q$$

During the turbining phase, the recovered power P_t is :

$$P_t = \rho g \left(H_b - \delta H^{"} \right) \eta_t$$

With :

η_t turbine efficiency,

$\delta H^{"}$ pressure drop in the circuit during turbine operation.

The efficiency of a pumped-storage cycle, where the same volume V of water is exchanged between the two reservoirs, can be derived from the two previous equations by integrating them over each phase (since H_b, Q, and the efficiencies vary throughout the cycle).

If we consider a highly simplified case where all hydrodynamic characteristics (flow rate Q, as well as pump and turbine efficiencies) emain constant during both phases, and where the gross head H_b varies only negligibly throughout the cycle, the overall round-trip efficiency would be:

$$\frac{E_t}{E_p} = \frac{H_b - \delta H^{"}}{H_b + \delta H} \eta_p \eta_t$$

Due to hydraulic head losses, the overall efficiency is therefore slightly lower than the product of the pump and turbine efficiencies. These hydraulic losses can be reduced by adopting large-diameter conduits and tunnels, ensuring that the water velocity remains within reasonable limits.

1.3.1.3 Classification of PHS Plants

Several classification criteria can be considered.

a. Gravitational water inflow into the upper reservoir

A distinction is made between:

- **Pure PHS (Closed-loop PHS):** In these plants, the upper reservoir receives no water inflow other than what is delivered through pumping.
- **Mixed PHS (Open-loop PHS):** In these plants, the upper reservoir receives natural inflows from a watercourse, or via tunnels and pipes collecting runoff, or meltwater from ice and snow.

In this case, the facility is further characterized by the annual energy potential corresponding to this natural inflow (volume V) falling from the gross head H_b through the turbines.

b. Onshore and Offshore PHS

A further distinction is made between:

- **Onshore PHS:** These require the installation of two reservoirs at different altitudes (Figure 1). This is by far the most widely used technology.
- **Large Lake PHS:** A variant of onshore PHS that uses a large natural lake as the lower reservoir. Examples include Lake Michigan for the massive American Ludington station (1,872 MW, soon to be 2,170 MW) and Lake Geneva (*Lac Léman*) for the Swiss Hongrin-Léman station (240 MW, soon to be 480 MW).
- **Offshore" or Seawater PHS:** Systems where the sea serves as the lower reservoir. These are not covered in this article as they represent an emerging technology.
- **Other innovative PHS types:** Potential future developments, such as stations utilizing underground reservoirs combined with very high heads.

c. Cycle Duration

Finally, PHS plants are distinguished by their storage duration scale, which depends on the "**useful**" volume of transferable water and the maximum flow rate during pumping or turbining. In energetic terms, one can also consider the **time constant** T which is the ratio between the energy E transferable from one reservoir to another, and the pumping power P_p for example:

$$T = \frac{E}{P_p}$$

This ratio T represents the order of magnitude of the maximum pumping duration. PHS plants are thus categorized as:

- ✓ **Daily storage:** If this time constant is approximately a few hours. In this case, the PHS is designed for daily operation, particularly to exploit electricity price spreads between peak and off-peak hours.
- ✓ **Weekly storage:** If this time constant is in the tens of hours. The PHS can then operate based on weekly electricity price fluctuations.
- ✓ **Seasonal storage:** If the PHS is installed with a very large reservoir (such projects could be implemented in countries like Norway).

Exemple :

The German Goldisthal PHS plant is characterized by a maximum storable energy of **E= 8,5 GWh** and a turbining power of **P_t= 1 060 MW**. Its time scale (in turbining mode) is therefore approximately **T= 8 h**. ***It is thus classified as a daily storage PHS plant***.

I.3.1.4 Description of a Pumped Hydro Storage (PHS)

A Pumped Hydro Storage (PHS) facility comprises:

- **The two reservoirs** can be either natural or artificial. If they are artificial, they required the construction of embankments or dams. If they are natural, their capacity has often been increased through the use of one or more dams
- **The water intakes** in both reservoirs**.**
- **Underground tunnels and penstocks** connecting the two reservoirs to the pumping and turbining plant.
- **The powerhouse(s),** which are underground in the most recent designs, containing the pumps and turbines.
- **The pumps and turbines** can be replaced by reversible pump-turbine units that perform both functions. In the most modern facilities, variable-speed pump-turbines are used, allowing for flexible adjustment of electrical power in both pumping and turbining modes.

A hydraulic turbine is a rotating machine that drives the generator. Turbine efficiencies generally range between 80% and 90%. There are three main types of turbines: **Pelton**, **Francis**, and **Kaplan**..

✓ Pelton Turbines

The Pelton turbine is a type of water turbine developed by Lester Allan Pelton in the 1870s. It is generally utilized for power plants with high heads and low flow rates. Nozzles direct powerful, high-speed water jets against a rotating series of spoon-shaped buckets, also known as impulse blades, which are mounted around the circumferential rim of a drive wheel called the runner. When the water jet strikes the blades, the direction of the water's velocity is altered to follow the contours of the bucket. The impulse energy of the water

exerts a torque on the bucket and wheel system, causing the runner to rotate; the water jet itself performs a "U-turn" and exits through the outer sides of the bucket.

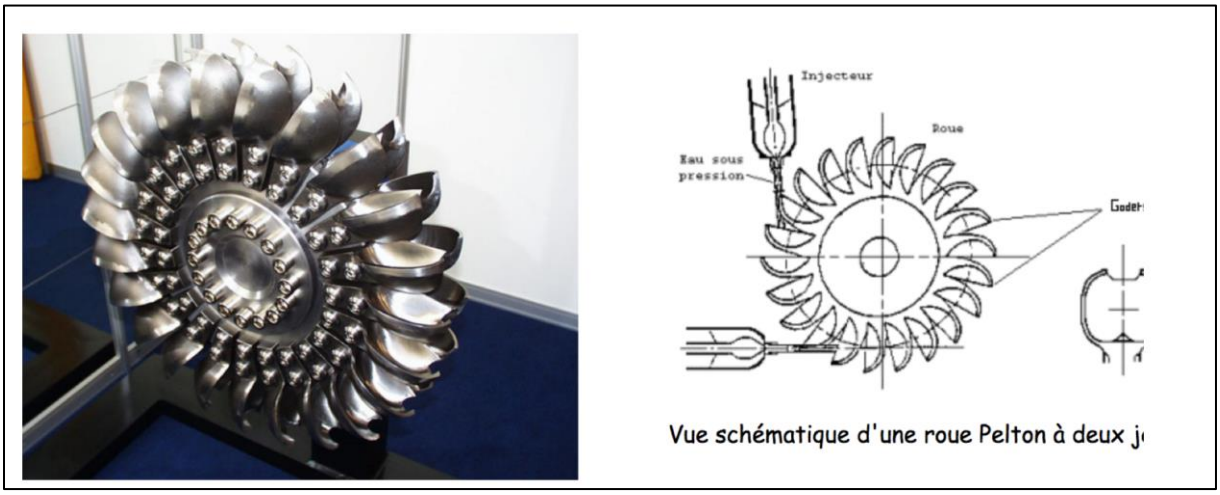


FIG 1.3 Pelton Turbines

Pelton turbines are preferred for hydroelectric power when the available water source has a relatively high head (10–2000 m) combined with low flow rates (0.04–1.5 m^3/s).

✓ Francis Turbines

The Franci's turbine was invented in the 19th century by James B. Francis and is utilized for medium heads and medium water flow rates. The Francis turbine is a type of reaction turbine, a category where the working fluid enters the turbine under immense pressure, and energy is extracted by the turbine blades from the fluid's flow. The turbine's draft tube is designed to help decelerate the water flow and recover pressure (Fig. I.4). The water flow is radial, moving from the outside toward the center.

Franci's turbines cover a medium head range (40–400 m) and medium flow rates (0.1–6 m^3/s). Their efficiency decreases as the flow rate drops. They can also be used for pumped storage, where the reservoir is filled by the turbine (acting as a pump) driven by the generator, which functions as a large electric motor during periods of low power demand.

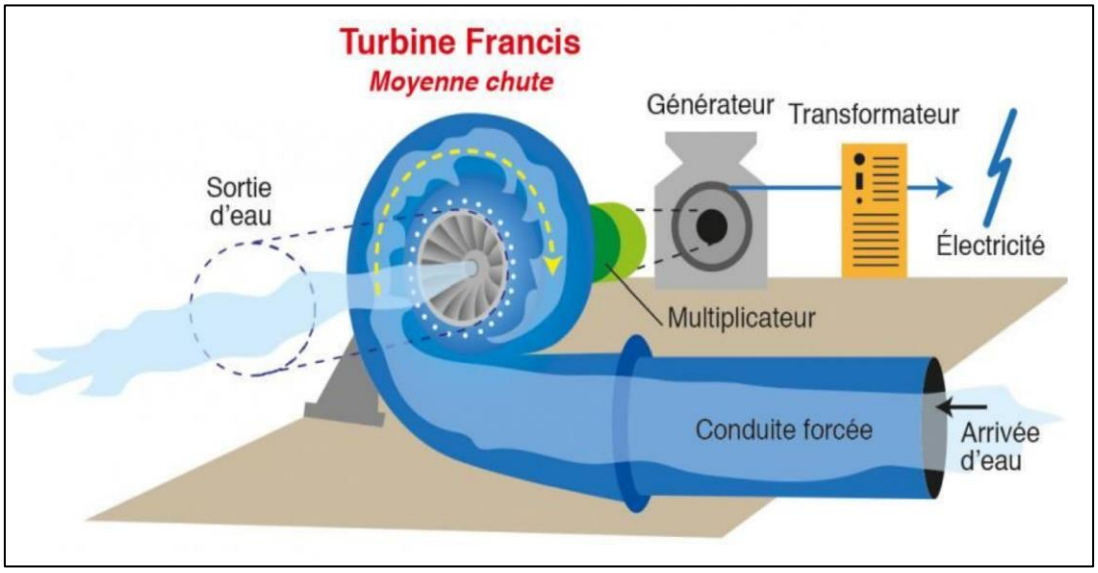


Fig I.4 Francis Turbines

✓ Kaplan Turbines

The Kaplan turbine was developed in 1913 by the Austrian professor Viktor Kaplan. It features adjustable blades and is utilized for low velocities and high flow rates. It is an inward-flow reaction turbine, meaning that the working fluid changes pressure as it moves through the turbine and surrenders its energy. The inlet is a scroll-shaped casing (volute) that wraps around the wicket gate. The water is directed tangentially through the wicket gate and spirals onto a propeller-shaped runner, causing it to rotate (Fig. I.5).

Kaplan turbines are widely used for electrical power generation. They cover the lowest head hydroelectric sites (10–30 m) and are particularly suited for high flow rate conditions (300–10,000 m^3/s). Large Kaplan turbines are individually designed for each site to operate at the highest possible efficiency (>90%). While they are very costly to design, manufacture, and install, they operate for decades.

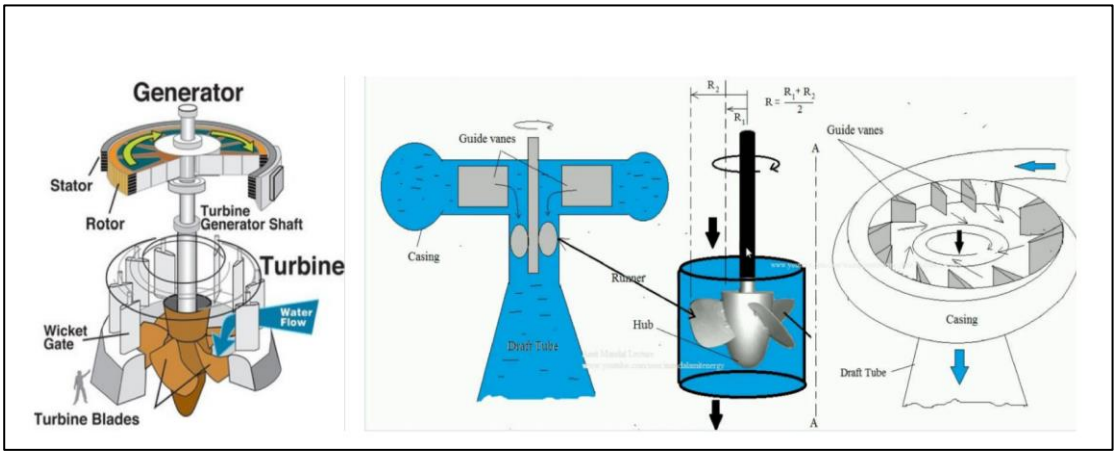


Fig I.5 Kaplan Turbines

✓ Cross-flow Turbines

In 1903, Anthony Michell developed the cross-flow turbine, which is utilized for low heads (10–70 m). Similar to other water turbines, water is admitted at the edge of the turbine. After passing through the runner, it exits from the opposite side. Passing through the runner twice provides higher efficiency (Fig. I.6). The cross-flow turbine is a low-speed machine well-suited for sites with varying heads (2–200 m) and moderate flow rates (0.03–16 m^3/s).

The maximum efficiency of a cross-flow turbine is slightly lower than that of Kaplan, Francis, or Pelton turbines. However, it offers a low cost and effective regulation. Since the water traverses the runner twice, it provides additional efficiency. Cross-flow turbines are primarily used in mini and micro-hydropower plants. A notable advantage is that as the water leaves the runner, it helps clean it of small debris and pollutants.

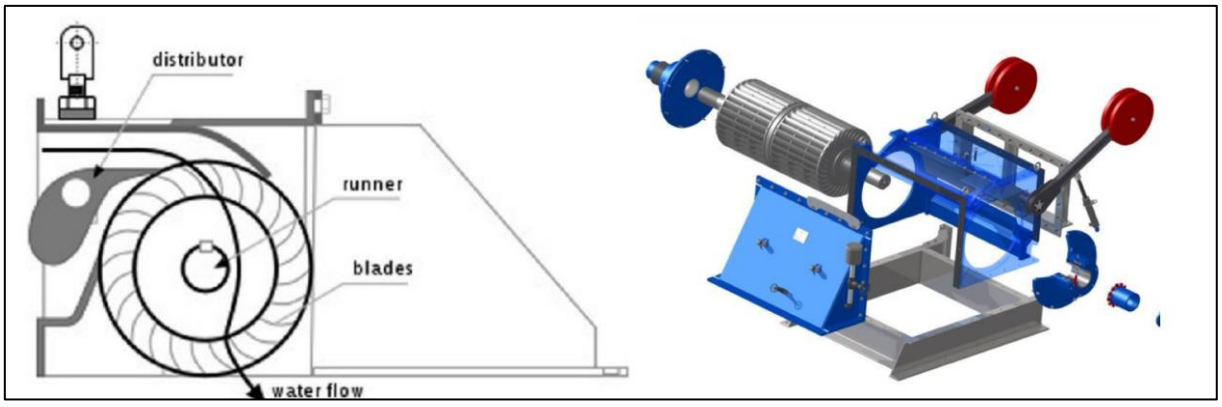


Fig I.6 Cross-flow turbine

Table I.2: Operating Head and Flow Rate Ranges for Each Turbine Type

TURBINE TYPE	HEAD RANGE	FLOW RATE RANGE
Pelton	10 - 2000 m	0.04 – 1.5 m^3/s
Francis	40 - 400 m	0.1-6 m^3/s
Kaplan	10 - 20 m	300-10000 m^3/s
Cross flow	2-200 m	0.03-16 m^3/s

- **Ancillary structures:** gates, surge tanks, as found in all hydroelectric developments

I.3.1.5 Co Construction and Operating Costs

a. Construction Costs

Today, two types of pumped-storage development projects can be distinguished:

- ✓ **Greenfield projects:** the construction of entirely new facilities
- ✓ **Retrofitting or expansion projects:** which involve adding pumping capabilities to existing hydroelectric plants or increasing the capacity of existing PHS facilities.

The construction cost includes the following items:

- ✓ **Civil Engineering:** dams, embankments, tunnels. For reference, civil engineering alone often accounts for 40% to 50% of the total project cost.
- ✓ **Mechanical Installations:** pumps, turbines, valves, penstocks.
- ✓ **Electrical Installations**.

These costs depend significantly on the specific conditions of each development project.

The construction period for a large-scale PHS plant is generally in the range of 7 to 10 years. This timeframe primarily depends on the scale of the civil engineering works, particularly the dams to be constructed.

b. Operating Costs

Operating costs include:

- ✓ **Energy Loss Costs:** The cost of the electrical energy lost during a pump-storage cycle: $E_p - E_t$;
- ✓ **Grid Connection and Usage Fees:** These are defined by the specific regulations of each country. In France, for instance, grid access costs are applied to both the pumped energy E_p *and the turbined energy* E_t, which creates an economic penalty for energy storage. In other countries, grid access costs are only applied to the net energy loss $E_p - E_t$.
- ✓ **Property and Miscellaneous Taxes:** These also vary from one country to another.
- ✓ **Maintenance and Labor Costs:** As with all hydroelectric facilities.

I.3.1.6 Social and Environmental Aspects

A pumped-storage hydropower plant helps limit the reliance on peak-load power plants, which typically consist of gas turbines. When used in conjunction with a fossil-fuel-based thermal fleet (such as coal-fired plants), it allows these plants to operate closer to their peak efficiency point, resulting in energy savings and reduced CO_2 emissions. Consequently, such a facility generally leads to fossil fuel conservation, thereby limiting CO_2 emissions and other combustion by-products in the atmosphere. Furthermore, the development of PHS in the 21st century is part of a global framework for the expansion of renewable energy.

However, several local environmental and societal aspects must be taken into account, which are similar to those of other hydroelectric developments.

I.3.2 Thermal Energy Storage

Humanity has always stored energy in the form of heat through simple practices, such as heating a stone in the sun and subsequently using it for heating or cooking.

I.3.2.1 Heat Transfer

Heat transfer is one of the most common modes of energy exchange; it occurs naturally between two systems characterized by a temperature difference, regardless of the medium. Thermal exchange involves a heat flow rate (in Watts), which expresses the amount of energy passing through a given surface every second, or locally, a heat flux density (in W/m^2), representing the amount of energy transmitted per second through a unit surface area. Mathematical models of various transport phenomena link heat flows to the temperatures existing at specific locations, allowing for the computational prediction of behavior within a structural element under various circumstances. This transfer mode is considered steady-state when temperatures at different points remain constant—that is, independent of time.

I.3.2.2 Different Heat Transfer Modes

There are three modes of heat transfer: **conduction**, **convection**, and **radiation.**

Conduction: Heat propagates within a body from particle to particle through intermolecular interactions, while the particles remain at rest.

Convection: Heat transfer occurs between a fluid (liquid or gas) and a solid body, or vice-versa (for example, from air to a wall), with the particles moving relative to one another.

Radiation: This involves energy transport via electromagnetic waves. Thermal radiation occurs from one body to another without requiring a physical medium

I.3.2.3 Heat Transfer by Conduction:

Conduction is the transmission of heat through matter via molecular vibration. It primarily concerns solids, but also liquids and gases, for which it is often negligible compared to convection or radiation.

1) Fourier's Law

It expresses the proportionality between cause and effect:

Cause: Temperature gradient **dθ/dx**

Effect: Heat flow rate **(i.e., heat flux).**

$$\varphi = -\lambda \frac{d\theta}{dx} \quad (\mathrm{W/m2}) \qquad \phi = -\lambda S \frac{d\theta}{dx} \quad (\mathrm{W})$$

2) Thermal Conductivity

Thermal conductivity depends on the material's structure, density, temperature, humidity, and pressure. These represent average values under real-world conditions.

3) Contact Temperature

When two bodies at different temperatures are brought into contact, the contact temperature is the temperature at the interface. It depends on the thermal effusivity of both materials.

I.3.2.4 Definition of thermal energy storage

Storage is an essential component of any solar system, as energy supply and demand are generally out of phase with one another. This is particularly the case with heating systems. Examining such a system on a daily scale reveals that, on average, heating requirements increase at night, whereas solar gains are only available during the day (see Figure I.7). The purpose of storage is therefore to capture the surplus energy marked (+) for use during the night (-).

The problem of the phase shift (Figure I.7) between heat production and user demand can be resolved by integrating a thermal accumulator within the thermodynamic conversion chain.

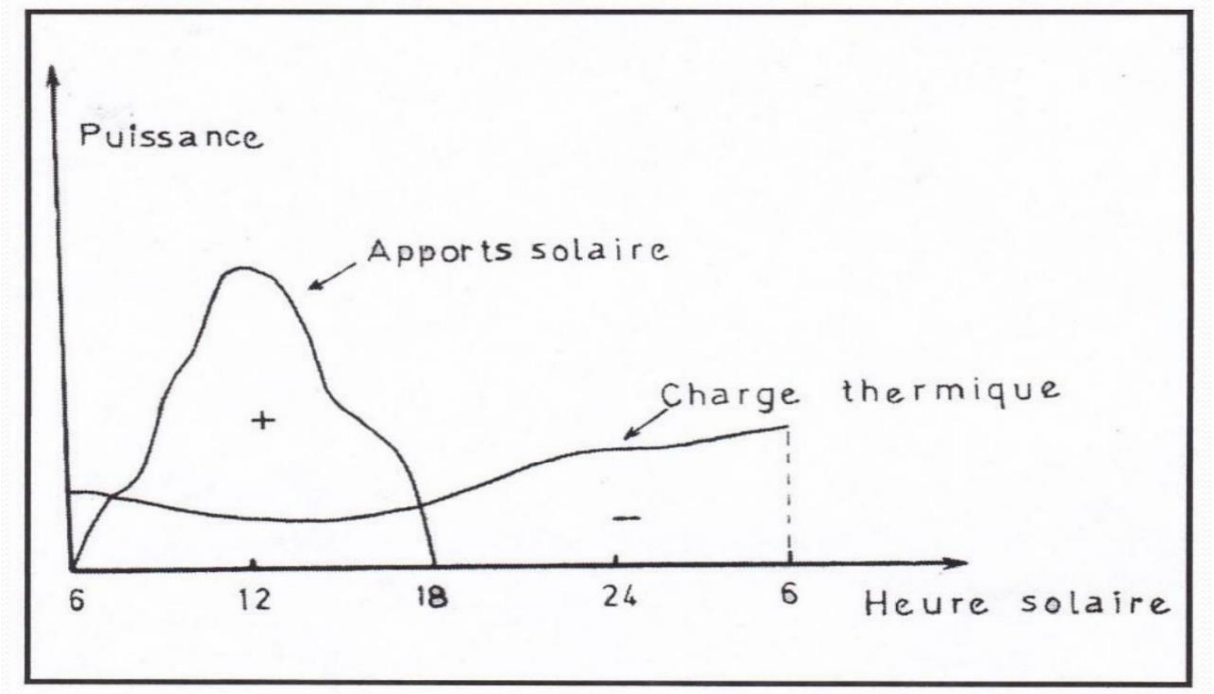


Fig I.7. Inputs and needs over a day

Depending on the storage capacity, we can distinguish between:

- **Very short-term storage (minutes to hours):** Small electric tanks (approximately 30L) installed at draw-off points allow for the temporary storage of a small amount of hot water while minimizing distribution losses in the pipes**.**
- **Short-term storage (days):** Solar thermal systems require at least diurnal storage, typically implemented using water tanks.
- **Medium-term storage (weeks):** Medium-term storage (a week or more) is of limited interest. It sometimes occurs in seasonal stocks that are undersized (or inefficient), though it is not a primary objective.
- **Long-term storage (inter-seasonal):** This refers to capacities capable of storing surplus energy for use in winter. Seasonal storage can be achieved through various methods.

Over the past 20 years, four storage techniques have become established (Fig I.8)

1. hermal storage in the ground: in a water reservoir (A),
2. By geothermal heat exchangers (B),
3. By aquifers(C)

4. In a water + gravel reservoir (D): water storage, gravel bed storage, geothermal borehole storage, and aquifer storage.

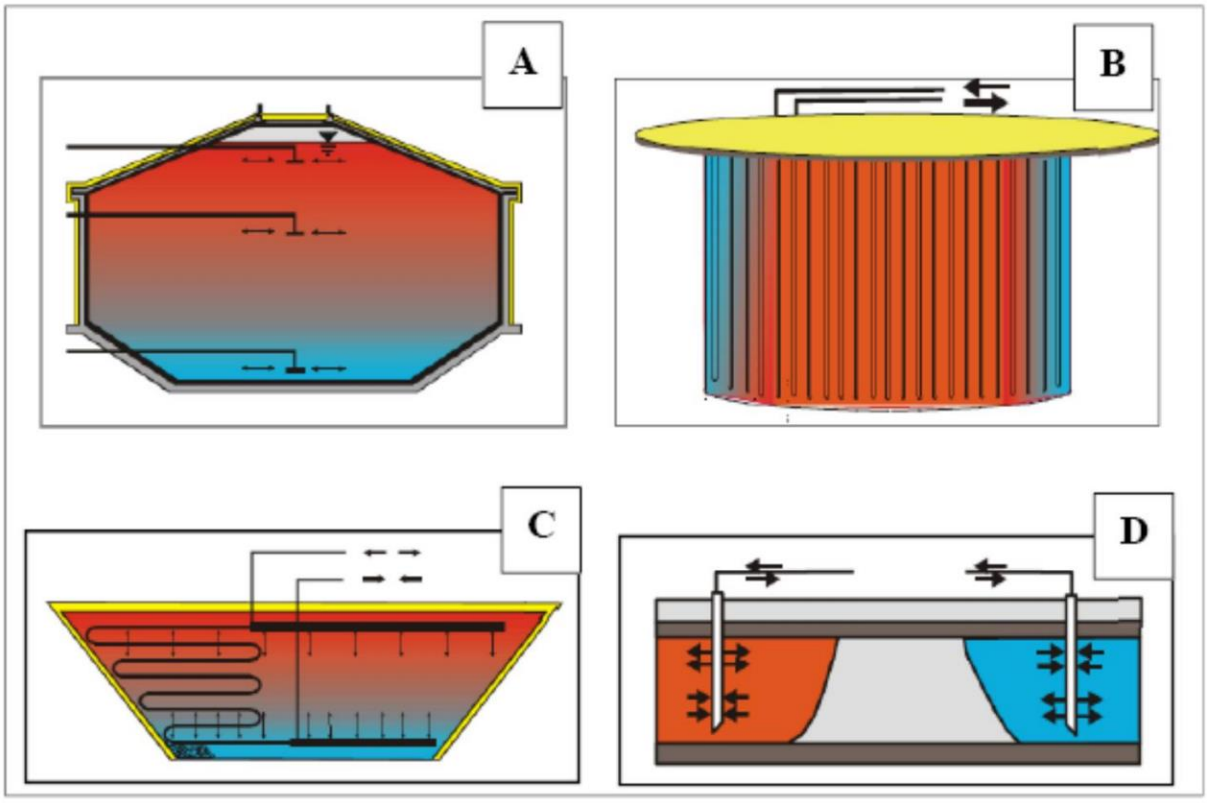


Fig I.8 The 4 techniques of seasonal storage

I.3.2.5 The Different Physical Processes of Thermal Energy Storage

A distinction should be made between three storage modes:

a. **Sensible Heat Storage:** A long-standing method for storing thermal energy (such as the hot water bottle or storage heating) consists of preheating a body to a high temperature and subsequently bringing it into contact with a lower-temperature system for use.

Thus, at constant pressure, if a body (generally solid or liquid) of mass M and specific heat capacity c(T) is heated from an initial temperatureT_1 to a final temperature T_2, the stored energy is given by its enthalpy variation:

$$H_2 - H_1 = \int_{T_1}^{T_2} Mc(T)dT$$

Or to simplify c(T)= cst

$$H_2 - H_1 = Mc(T_2 - T_1)$$

f, subsequently, this body is brought into contact with a user system at a temperature $T'_1 < T_2$, it can release a quantity of energy equal to:

$$Mc(T_2 - T_1') - \left|Q_{perte}\right|$$

Where Q_{perte} *r*epresents the heat loss during storage at temperature T_2 or during the heat exchange process, which we aim to minimize.

According to thermodynamic conventions, this heat exchange is negative, which explains the use of absolute value signs.

This process is referred to as sensible heat storage. It should be noted that if, during the storage operation, we have:

- $T_2 > T_1$ this is referred to as heat storage (or hot storage);
- $T_2 < T_1$ this is referred to as **cold storage** (in this case, the system at T_1 releases energy to the storage medium

Energy discharge toward lower temperatures constitutes **heat discharging** in the first case, while energy discharge toward higher temperatures corresponds to **cold discharging** in the second. It should be noted, however, that unless specified otherwise, temperature levels are typically defined relative to **ambient temperature**. Consequently, for applications above ambient temperature (such as heating), it is most likely considered **heat storage**, whereas **sub-ambient** applications would involve **cold storage**. The primary materials used for sensible heat storage include liquids such as water or **glycol-water mixtures** (liquid tanks) and solids such as stones (e.g., granite for underground storage).

b. Latent Heat Storage: The stored heat results in both a temperature variation and a phase change of the storage medium (e.g., solid-liquid). The material changes its phase at a constant temperature, either releasing or accumulating heat depending on the direction of the transformation (average capacity of 200 MJ/m³).

Let us assume that the storage medium is a pure solid with a melting point (T_m) such that [condition]. The stored energy, still at constant pressure, would be given by the enthalpy variation:

$$H_2 - H_1 = \int_{T_1}^{T_F} Mc^s(T)\,dT + ML_F(T_F) + \int_{T_F}^{T_2} Mc^L(T)\,dT$$

With c^S (T) et c^L (T) specific heat capacities of the body when it is in the solid or liquid state, respectively. If these heat capacities can be considered constant and equal to c^S or c^L , the relationship simplifies to:

$$H_2 - H_1 = Mc^s(T_F - T_1) + ML_F(T_F) + Mc^L(T_2 - T_F)$$

And

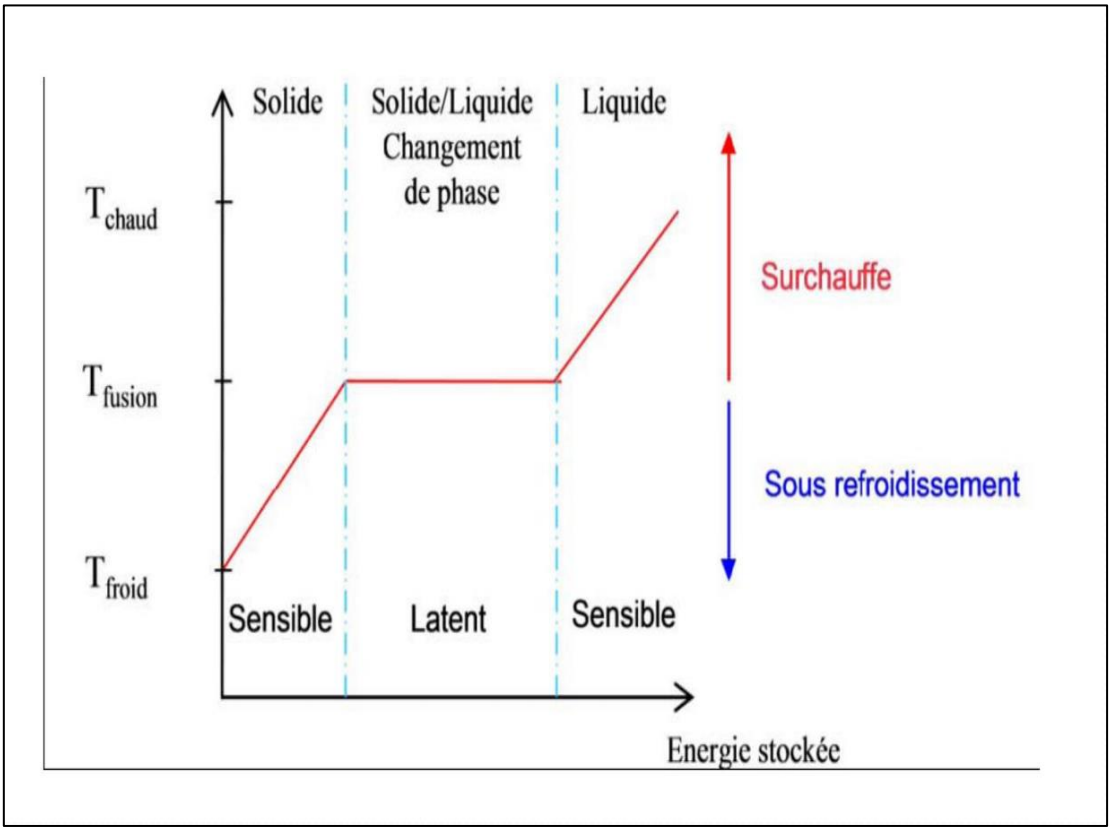
$$L_F(T_F) = h^L(T_F) - h^S(T_F) \succ 0$$

With:

h^L (T_F) and h^S (T_F) respectively the specific enthalpies of the liquid and solid states at the equilibrium temperature T_F.

$L_F(T_F)$, the enthalpy variation during melting, is called latent heat.

It is noteworthy that the term ML_F is generally much larger than the other terms in the right-hand side of the equation. Indeed, for an equivalent mass, the energy stored via latent heat is significantly greater than that stored via sensible heat.



Example:

If ice is heated from-1°C à +1°C, given that:

C^s= 2 176 J/kg.K soit 0.60 kWh/m^3.K

C^L= 4 185 J/kg.K soit 1.16 kWh/m^3.K

L_F= 224 800 J/kg.K soit 0.60 kWh/m^3.K

For 1 kg of ice, a total energy of 331,161 J is stored, which is equivalent to 94.8 kWh/m³.K. To store the same amount of energy by heating an equivalent mass of water starting from 0°C, it would have to be heated to 81.5°C.

Thus, the advantage of latent heat storage is significant, as it allows for the storage of larger quantities of energy with lower masses and smaller temperature variations. However, it can be expected to require more sophisticated technology than sensible heat storage.

c. **Reaction Heat Storage:** The stored heat triggers a chemical modification of the storage medium through a reversible endothermic reaction. The reverse reaction, which is inherently exothermic, releases the stored heat (average capacity of 700 MJ/m³).

Several studies have been dedicated to thermochemical storage. It consists of utilizing an endothermic chemical reaction. By supplying energy, the equilibrium shifts to the right; then, through contact with a lower-temperature source, it shifts back to the left, releasing the reaction energy.

Although the reaction enthalpy is relatively high (105 kJ/mol), the equilibrium shift is generally insufficient. For instance, it is found that the energy resulting from the equilibrium shift accounts for less than 10% of the energy stored via sensible heat. Consequently, the gain is negligible, and this type of storage appears to have remained at the laboratory stage.

I.3.2.6 Advantages and Disadvantages of Latent Heat Storage

The main advantages are:

- Electricity consumption at night to take advantage of off-peak tariffs for storage, with discharge occurring during periods when electricity is expensive.
- **investment optimization** for a refrigeration unit that operates steadily at a power level corresponding to the reduced daytime production or nighttime storage, rather than sizing it to meet **peak demand** over a short period. More generally, this leads to **peak shaving**, preventing frequent and sudden start-stop cycles which are not recommended for refrigeration units.

An additional function is:

- **Safety and Backup:** In the event of a power failure, only minimal equipment is needed to operate the discharge process, instead of a backup generator sized for the full peak load,

Although these advantages could theoretically apply to sensible heat storage, the previous calculation example shows that it would require much larger volumes of liquids or solids, or excessive temperature differences incompatible with the standard operation of refrigeration units.

I.3.3 Compressed Air Energy Storage (CAES)

The principle of CAES (Compressed Air Energy Storage), as illustrated in Fig. I.9, consists of using surplus electrical energy to compress air, which is then stored in an underground reservoir. The compression process generates heat. When needed, the air can be released into a combustion chamber within a gas turbine to generate electricity.

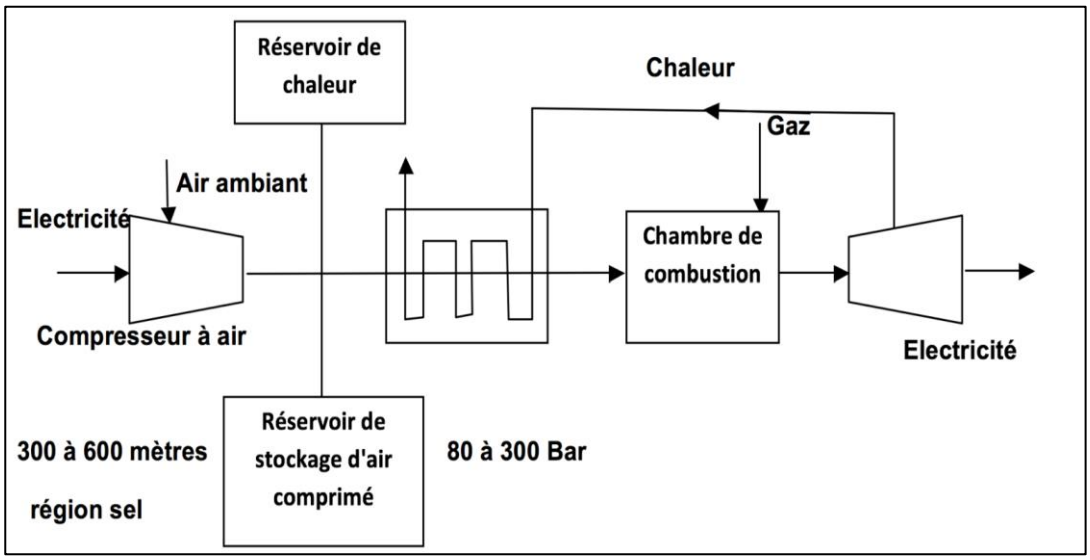


Fig I.9 Principe de fonctionnement des CAES

I.3.3.1 Types of CAES Systems

a. Conventional (Diabatic)

The hot compressed air at the compressor outlet is sent directly into a storage cavern. The efficiency of conventional systems is approximately 50%.

b. diabatic (A-CAES)

Adiabatic CAES systems are similar to conventional ones but also include a thermal energy storage (TES) system to capture the heat of compression. Their efficiency is approximately 70%.

c. Isothermal

Isothermal CAES involves extracting heat from the air continuously during the compression process (rather than after compression, as in adiabatic systems). Its efficiency is approximately 95%.

I.3.3.2 Flywheels

hey are used for inertial energy storage, where energy is stored in the form of kinetic energy on a disk rotating at speeds of 130 to 265 rps (revolutions per second).

I.3.3.2.1 Operating Principle

To store energy, the power converter controls the electrical machine so that it functions as a motor; the flywheel spins up and accelerates, thereby storing energy. Then, the converter controls the electrical machine to function as a generator; the flywheel is decelerated (braked), and the energy is fed back into the grid. Fig. I.10 illustrates this principle.

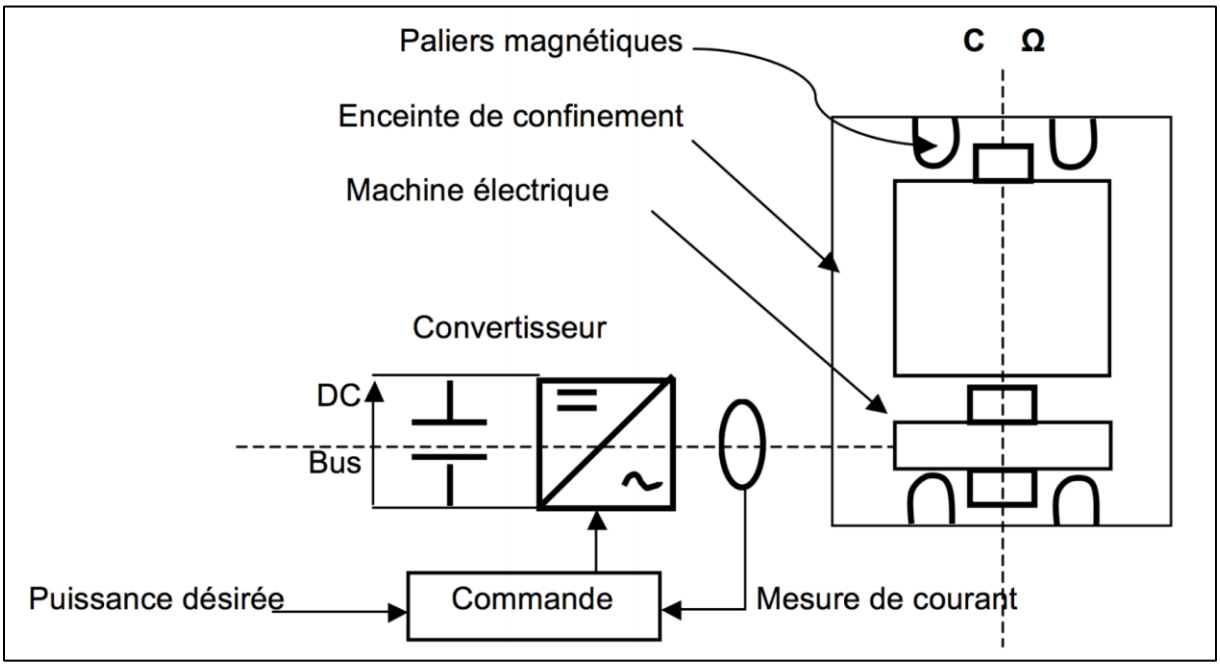


Fig. I.10 Operation of a flywheel

Calculation of Storable Energy

Recall that the kinetic energy of a mass m in translation at a velocity v is given by:

$$E_c=1/2\ mv^2$$

The rotational kinetic energy of a system with a moment of inertia J at an angular velocity Ω is given by:

$$E_c=1/2\ J\Omega^2$$

The moment of inertia of the rotating parts for several basic cases is provided in Table 1.3

Table I.3: Moment of Inertia for Common Geometric Shapes

Systèmes	Moment d'inertie
Masse d'une particule	$m.r^2$
Cylindre plein de masse M	$\frac{1}{2}M.r^2$
Cylindre creux de masse M	$\frac{1}{2}M(R_{int}^2 + R_{ext}^2)$
Barre stationnaire de masse M et de longueur L tournant auteur de son centre de gravité	$\frac{1}{12}ML^2$

It should be noted that increasing the stored kinetic energy requires both a high rotational speed and a large moment of inertia. However, design constraints are limited by the flywheel's peripheral velocity V_p where

$$V_p=\Omega R_r$$

R_r radius of the flywheel.

Thus, the stored energy depends directly on the maximum peripheral velocity V_{pmax} allowed by the rotating part, taking into account its mechanical tensile strength at the yield point R_e, its density ξ and its geometry.

$$V_{p\max} = k_v\sqrt{\frac{R_e}{\rho}}$$

k_v: velocity coefficient related to the stress concentration factor within the flywheel. the k_v for a simple cylinder with an inner radius R_{int} and an outer radius R_{ex} is given by:

$$kv=\begin{cases}\dfrac{3+v}{8}\rightarrow \textbf{Solid cylinder}\\ \dfrac{3+v}{4}\left(1+\dfrac{1-v}{3+v}\alpha^2\right)\rightarrow \textbf{Hollow cylinder}\\ \alpha=\dfrac{R_{\text{int}}}{R_{ex}}\end{cases}$$

Where v corresponds to the Poisson's ratio.

I.4 Conclusion:

The comprehensive analysis of energy storage technologies demonstrates that the global transition toward a decarbonized energy mix does not rely on a single "silver bullet" solution. Instead, it necessitates a technological complementarity dictated by specific power scales, discharge durations, and geographical constraints.

Pumped Hydro Storage (PHS) remains the bedrock of utility-scale energy management. Beyond its primary role in arbitrage (peak/off-peak price spreads), its evolution into variable-speed technology provides the essential ancillary services—such as frequency regulation and rapid backup—required to mitigate the inherent intermittency of solar and wind energy. As the most mature and economical large-scale method, PHS is the benchmark for grid-level storage efficiency (75-80%).

The diversification of storage modes—Mechanical, Thermal, and Chemical—addresses different segments of the energy chain:

- **Thermal Innovation:** While sensible heat storage is traditional, latent heat storage represents a significant leap in energy density. By utilizing phase-change materials, it allows for greater energy accumulation with smaller masses and minimal temperature variations, which is critical for optimizing thermodynamic cycles.
- **Kinetic and Compressed Air:** Technologies such as Flywheels offer instantaneous power response for inertial stability, while CAES (specifically Isothermal or Adiabatic types) provides a scalable alternative for bulk storage when geographical conditions for hydro are unavailable.

From an engineering perspective, the efficiency of a storage facility is not a fixed intrinsic value but a dynamic variable dependent on cycle optimization, hydraulic head loss reduction, and thermal management. Strategically, these systems serve as the primary lever for decarbonization; by allowing base-load plants to operate at peak efficiency and reducing reliance on fossil-fuel gas turbines, storage directly correlates with a reduction in global

The mastery of energy storage lies in the ability to hybridize these technologies matching the physics of the storage medium to the specific temporal and economic demands of the modern smart grid.

CHAPTER II

Fuel Cells

II.1 Introduction

Fuel cell technology offers significant potential for a wide range of applications, including microgrids, transportation, the automotive market, military projects, and space missions.

The first part of this chapter is dedicated to an overview of fuel cells, their core components, their operating principles, and the various existing types. The second part describes hydrogen production and storage methods.

Finally, we will present the diverse applications of this technology within the transportation sector and renewable energy systems.

II.2 Fuel Cell Structure

A fuel cell is composed of the following core components:

- Two electrode compartments separated by a polymer electrolyte membrane, consisting of an oxidizing anode (electron emitter) and a cathode (electron collector);
- A polymer electrolyte membrane which, together with the electrodes, forms the Membrane Electrode Assembly (MEA), preventing the crossover of gases and electrons from the anode to the cathode;
- Two bipolar plates that provide gas distribution (reactant supply) and ensure the removal of the produced water;
- Sealing gaskets that prevent the mixing of the fuel at the anode and the oxidant at the cathode, while also preventing leaks to the external environment.

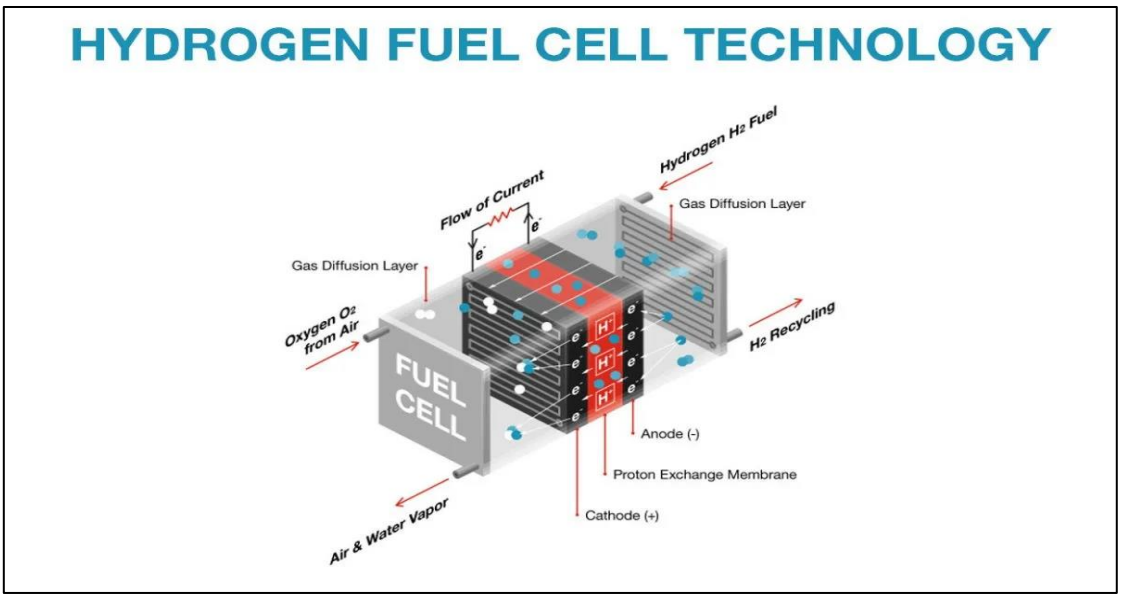


Fig II.1 Fuel Cell Architecture

II.3 Operating Principle

A fuel cell (FC) is an electrochemical energy generator consisting of two electrodes an electron-emitting anode and an electron-receiving cathode—separated by an electrolyte that allows ionic transport. A membrane prevents direct contact between the reactants at the anode and the cathode (Fig. II.2). This generator converts chemical energy into electrical energy through two simultaneous electrochemical reactions.

In a Proton Exchange Membrane Fuel Cell (PEMFC) supplied with hydrogen, the hydrogen is oxidized into protons and electrons at the anode. The protons migrate through the electrolyte toward the cathode. Since the membrane acts as an electrical insulator, the electrons are forced to travel through an external electrical circuit.

At the cathode, oxygen reacts with the protons to produce water, which is the only byproduct of a hydrogen-fueled cell. The hydrogen is oxidized at the anode into protons and electrons.

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

While oxygen is reduced at the cathode, the overall reaction within the fuel cell occurs as follows:

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

The total reaction in the cell:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

Using hydrogen and oxygen as reactants, the fuel cell produces electrical energy, heat, and water. While other fuels, electrolytes, and charge carriers exist for various types of fuel cells, the underlying principle remains the same.

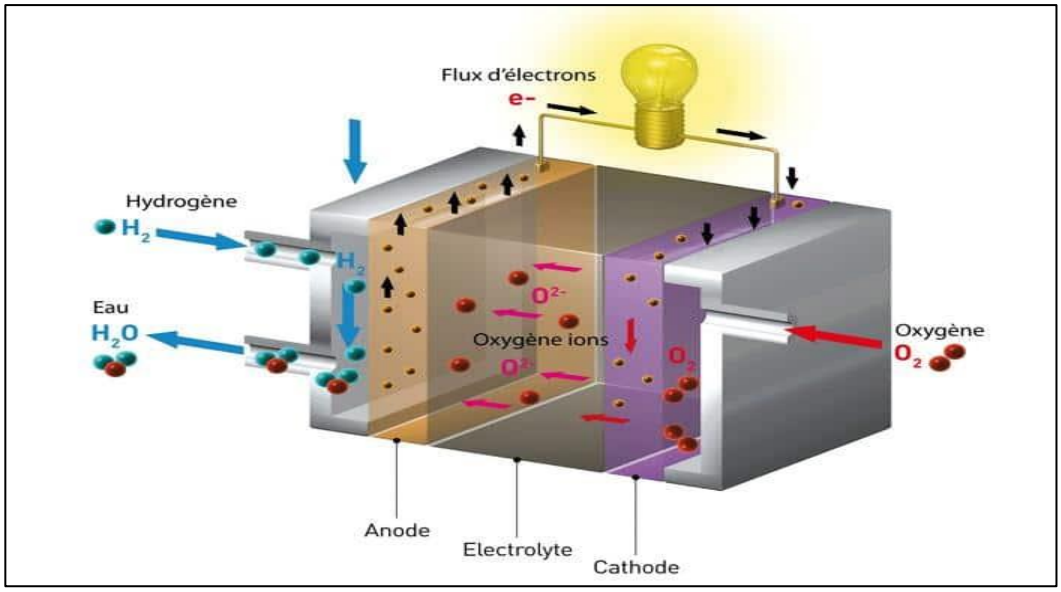


Fig II.2 Operating Principle of a Fuel Cell

The driving force of a fuel cell is the natural affinity toward a lower state of Gibbs free energy. Hydrogen and oxygen are unstable in each other's presence and spontaneously form water through a redox reaction.

The maximum theoretical voltage of a single fuel cell is less than 1 volt. For practical applications, multiple cells must operate together. Generally, this is achieved by connecting several cells in series to form a fuel cell stack. By varying the number and active area of the cells, the stack can be tailored to meet almost any power requirement.

II.4 Kinetics and Efficiency of a Fuel Cell

A fuel cell is an electrochemical energy converter. Its operation is based on the aforementioned electrochemical reactions, which occur simultaneously at the anode and the cathode.

More specifically, these reactions take place at the interface between the electrolyte (the ionic conductor) and the electrode (the electronic conductor). Since gases are involved in fuel cell electrochemical processes, the electrodes must be porous. This porous structure allows the gaseous reactants to reach the active sites and facilitates the removal of the produced water from the reaction zones.

It should be noted that these represent the overall (global) reactions; in practice, both involve several sequential and parallel intermediate steps.

The efficiency of a fuel cell is defined as the ratio between the produced electrical power and the power of the consumed hydrogen. Both quantities must be expressed in the same units, typically Watts (W) or kilowatts (kW).

The generated electrical power is simply the product of the output voltage and the current.

$$P=V.I$$

Where I represents the current in Amperes (A) and V is the cell potential in Volts (V). The hydrogen consumption rate is directly proportional to the current (according to Faraday's Law).

$$N_{H2} = \frac{1}{nF}$$

Where N_{H2} is expressed in moles per second mol /s

et $$W_{H2} = \Delta H \frac{1}{nF}$$

W_{H2} : The energy of consumed hydrogen in Joules per second .

ΔH : The maximum heating value of hydrogen (256Kj/mol)

It should be noted that $\Delta H \frac{1}{nF}$ is expressed in volts, and for ΔH =256Kj/mol it equals 1,482 V, which is defined as the thermoneutral potential.

By combining the equations above, the fuel cell efficiency is shown to be proportional to the cell potential.

$$\eta = \frac{V}{1,482}$$

The lower heating value efficiency η_{LHV} is defined as follows:

$$\eta_{LHV} = \frac{V}{1,254}$$

If hydrogen leaks or crossover occur, the actual fuel consumption will exceed the theoretical amount corresponding to the generated current. Consequently, the real efficiency of the fuel cell will be slightly lower than the previously calculated theoretical value.

The overall fuel cell efficiency is therefore the product of the voltage efficiency and the current (or Faradaic) efficiency.

$$\eta = \frac{V}{1,482}\frac{i}{\left(i + i_{loss}\right)}$$

II.5 Different Types of Fuel Cells

II.5.1 Polymer Electrolyte Membrane Fuel Cells (PEM)

Polymer Electrolyte Membrane fuel cells (PEM) utilize a proton-conducting polymer membrane as their electrolyte. Hydrogen is typically used as the fuel.

These cells operate at relatively low temperatures and can rapidly modulate their output to meet changing power demands. PEM fuel cells are the primary candidates for powering automobiles. They can also be used for stationary power generation.

However, due to their low operating temperature, they cannot directly utilize hydrocarbon fuels, such as natural gas, liquefied natural gas, or ethanol. These fuels must be converted into hydrogen in a fuel reformer to be usable by a PEM fuel cell.

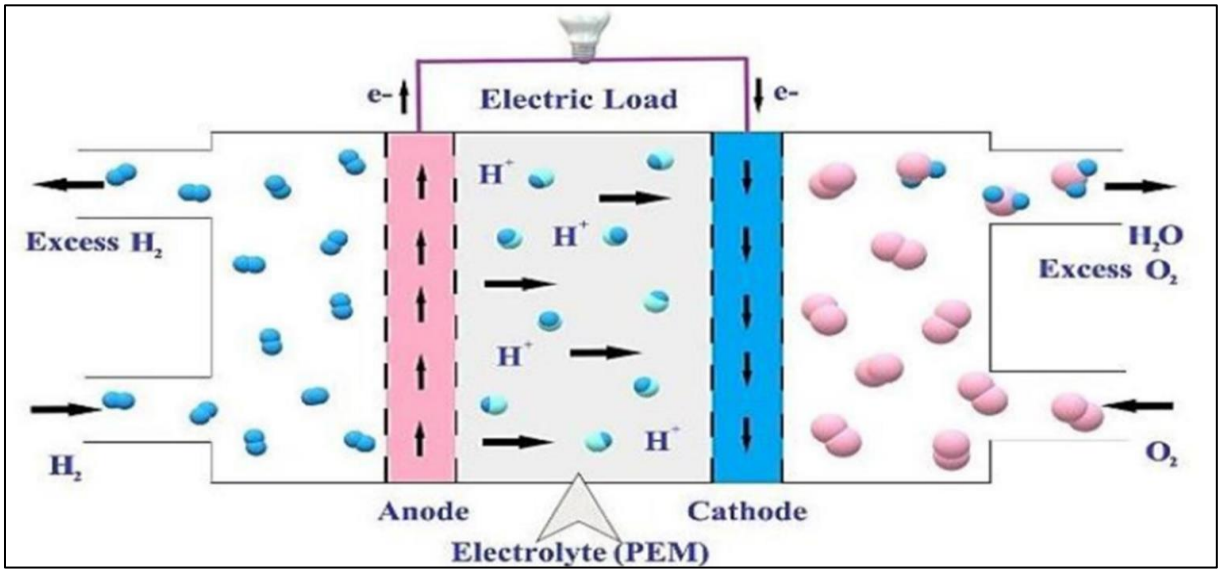
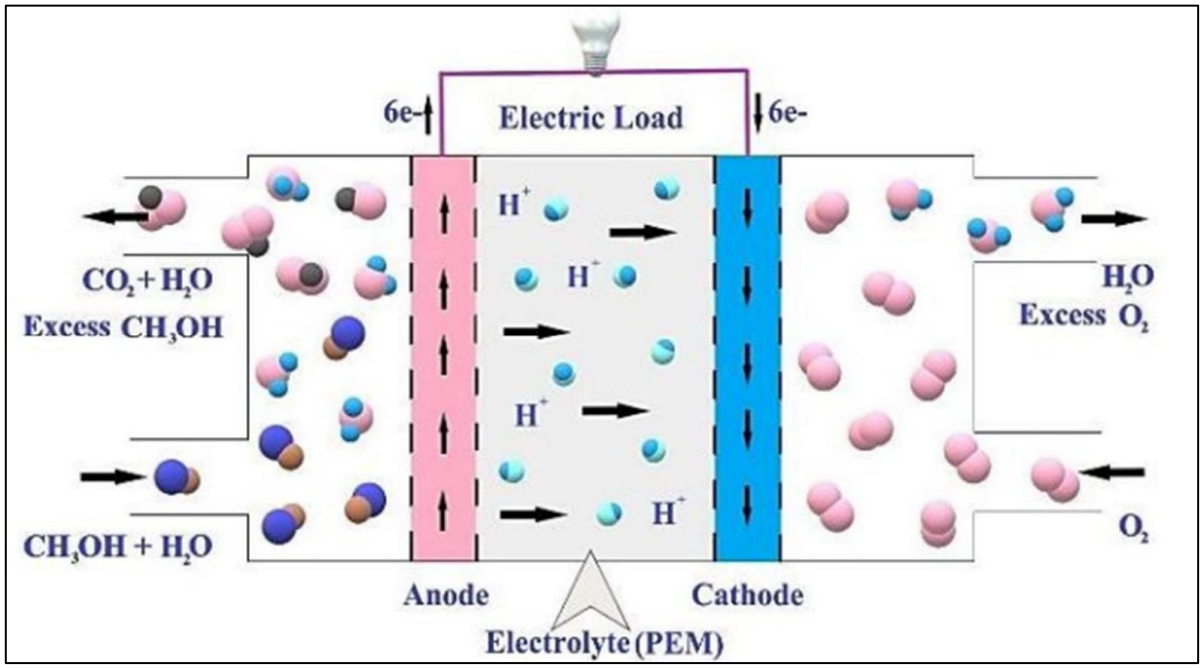


Fig II.3: Operating Principle of a PEM Fuel Cell

II.5.2 Direct Methanol Fuel Cells (DMFC)

Direct Methanol Fuel Cells (DMFC) are similar to PEM fuel cells in that they utilize a proton-conducting polymer membrane as their electrolyte. However, DMFCs use liquid methanol directly at the anode, which eliminates the requirement for a fuel reformer.

DMFCs are particularly attractive for powering portable electronic devices, such as laptop computers and battery chargers. Methanol offers a higher energy density than hydrogen, making it an advantageous fuel for portable applications.



FigII.4: Operating Principle of DMFC.

The half-reactions occurring at the electrodes are as follows:

At the Anode:	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$
At the Cathode:	$^3/_2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$
Overall Reaction:	$CH_3OH + {}^3/_2O_2 \rightarrow 2H_2O + CO_2 +$ **Electricity + Heat**

II.5.3 Alkaline Fuel Cells (AFC)

Alkaline Fuel Cells (AFCs) utilize an alkaline electrolyte, such as aqueous potassium hydroxide (KOH), or an alkaline membrane that conducts hydroxide ions (OH^-) instead of protons (H^+).

Originally deployed by NASA for space missions (such as the Apollo and Space Shuttle programs), alkaline fuel cells are now finding new applications, including portable power systems.

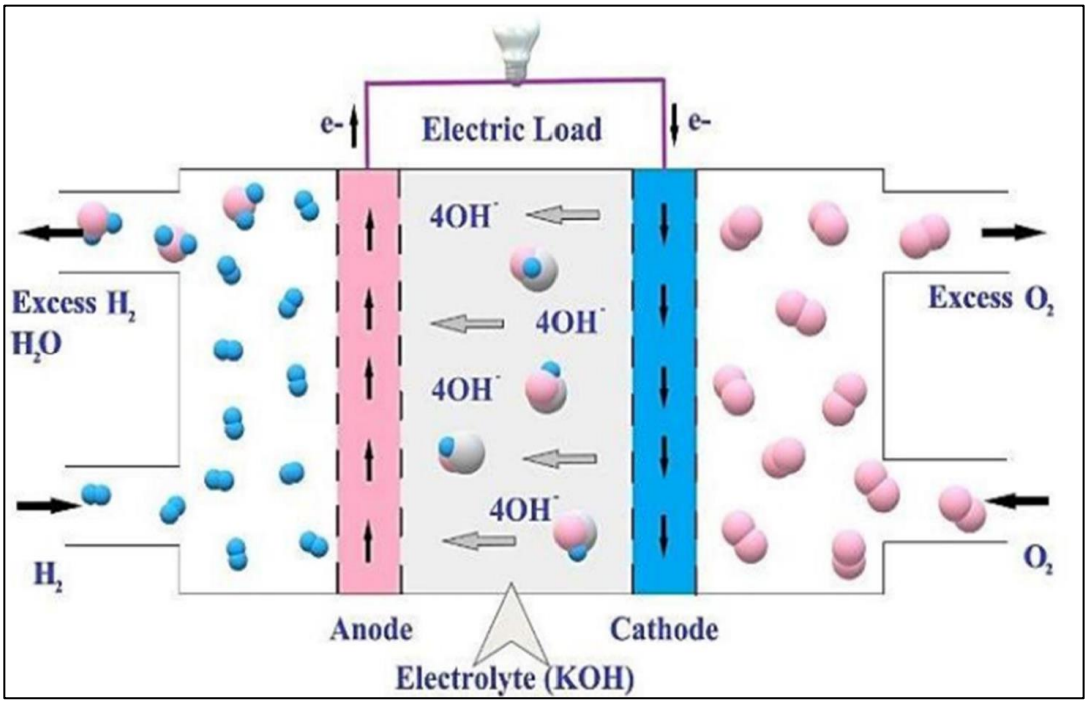


Fig II.5: Operating Principle of AFC.

The half-reactions occurring at the electrodes are as follows:

At the Anode:	$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$
At the Cathode:	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Overall Reaction:	$O_2 + 2H_2 \rightarrow 2H_2O +$ **Electricity + Heat**

II.5.4 Phosphoric Acid Fuel Cells (PAFC)

Phosphoric Acid Fuel Cells (PAFCs) utilize a phosphoric acid electrolyte that conducts protons, which are held within a porous matrix. These cells operate at temperatures of approximately 200°C.

They are typically deployed in modules of 400 kW or larger and are used for power generation in hotels, hospitals, grocery stores, and office buildings, where the byproduct heat can also be utilized. Phosphoric acid can also be immobilized within polymer membranes; fuel cells using these membranes are particularly attractive for specific stationary power applications.

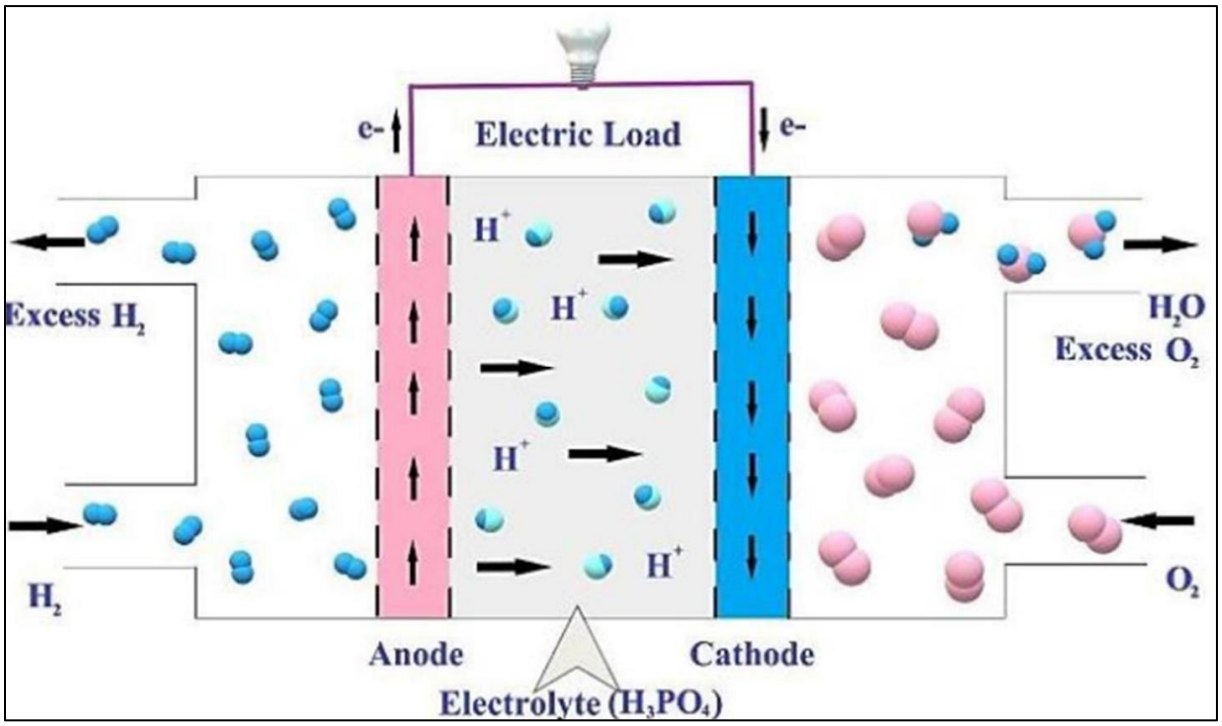


Fig II.6: Operating Principle of PAFC.

The half-reactions occurring at the electrodes are as follows:

At the Anode:	$H_2 \rightarrow 2H^+ + 2e^-$
At the Cathode:	$^1/_2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Overall Reaction:	$H_2 + {}^1/_2O_2 \rightarrow H_2O +$ **Electricity + Heat**

II.5.5 Molten Carbonate Fuel Cells (MCFC)

Molten Carbonate Fuel Cells (MCFCs) utilize a molten carbonate salt electrolyte immobilized within a porous matrix, which conducts carbonate ions CO_3^{-2}). They are already deployed in various medium-to-large scale stationary applications, where their high efficiency results in significant net energy savings.

Their high-temperature operation (approximately 600°C) enables internal reforming of fuels such as natural gas and biogas.

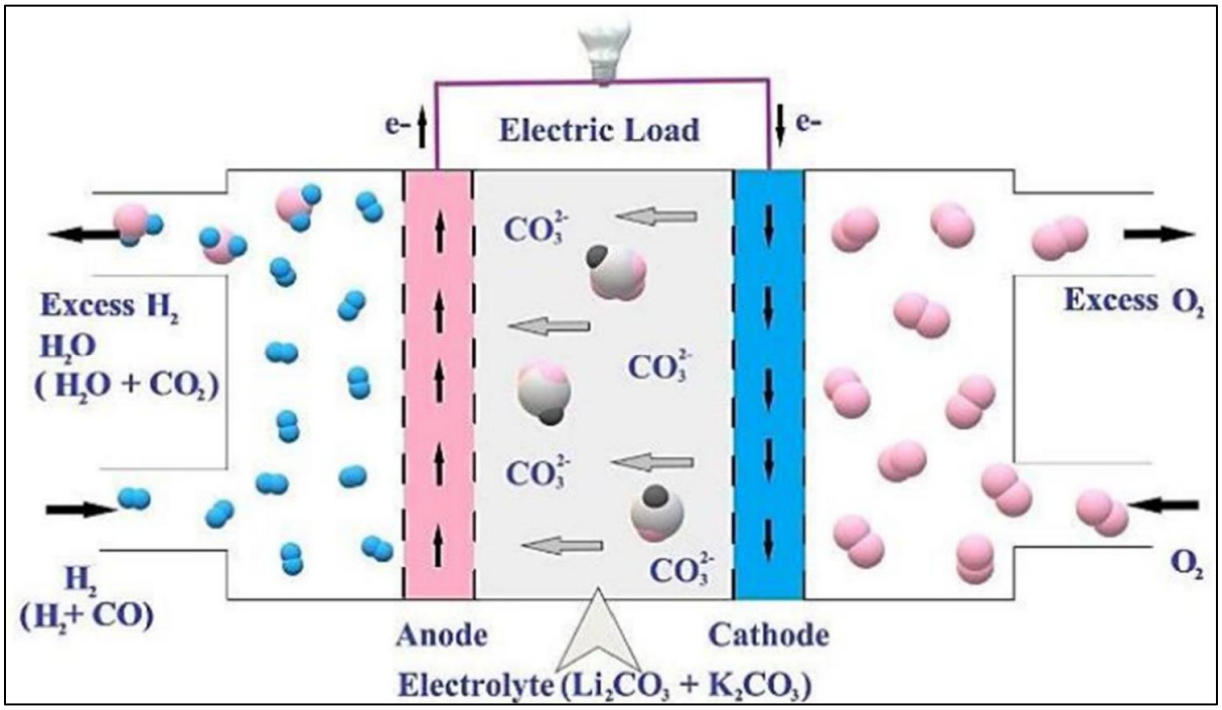


Fig II.7: Operating Principle of MCFC.

The half-reactions occurring at the electrodes are as follows:

At the Anode:	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$
At the Cathode:	$^1/_2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
Overall Reaction:	$H_2 + {}^1/_2O_2 \rightarrow H_2O +$ **Electricity + Heat**

II.5.6 Solid Oxide Fuel Cells (SOFC)

Solid Oxide Fuel Cells (SOFCs) utilize a thin, solid ceramic layer as an electrolyte that conducts oxide ions (O^{-2}). They are being developed for various stationary power applications, as well as for auxiliary power units (APUs) in heavy-duty trucks.

Operating at high temperatures (700°C - 1000°C) with zirconia-based electrolytes, and as low as 500°C with ceria-based electrolytes, these fuel cells are capable of internal reforming of natural gas and biogas. Furthermore, they can be integrated with gas turbines to achieve electrical efficiencies as high as 75%.

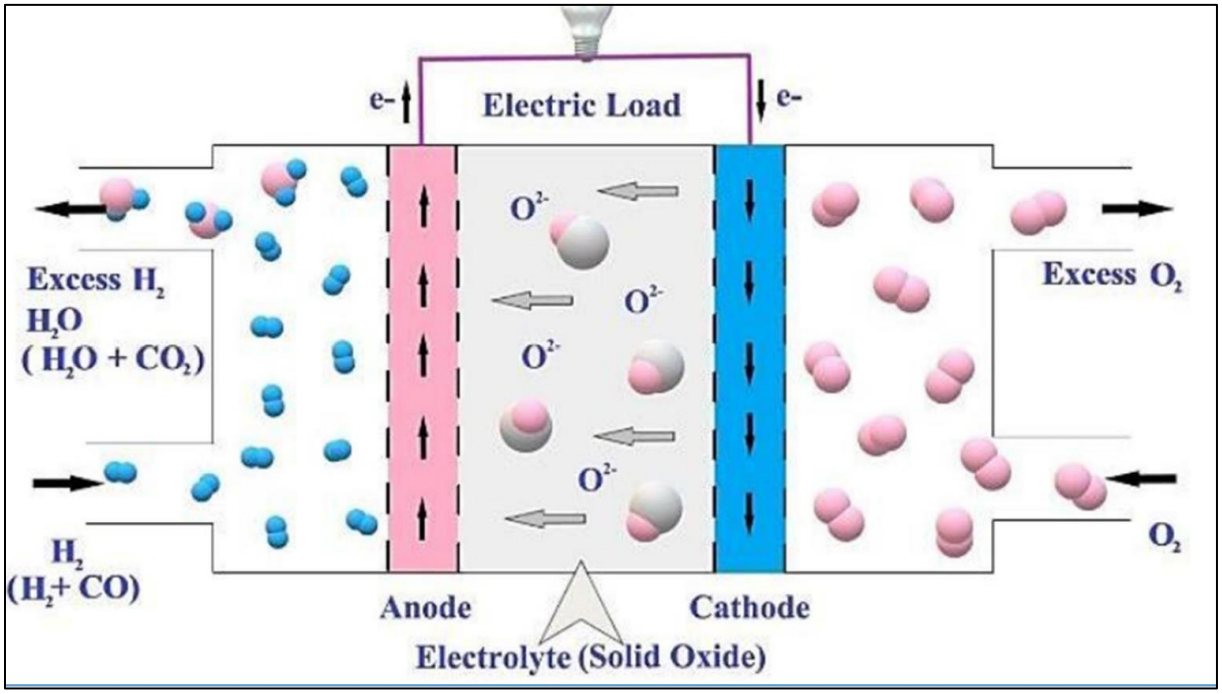


Fig II.8: Operating Principle of SOFC.

The half-reactions occurring at the electrodes are as follows:

At the Anode:	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$
At the Cathode:	$^1/_2O_2 + 2e^- \rightarrow O^{2-}$
Overall Reaction:	$H_2 + {}^1/_2O_2 \rightarrow H_2O +$ **Electricity + Heat**

II.5.7 Combined Heat and Power Fuel Cells (CHP)

Fuel cells generate both electricity and heat. This thermal energy can be harnessed to meet heating requirements, including domestic hot water (DHW) and space heating.

Combined Heat and Power (CHP) fuel cells are particularly attractive for residential and commercial buildings, where the overall efficiency can reach up to 90%. This high-efficiency operation leads to significant cost and energy savings while reducing greenhouse gas emissions.

II.5.8 Regenerative or Reversible Fuel Cells (URFC)

This type of fuel cell generates electricity from hydrogen and oxygen, but the process can be reversed by supplying electrical power to produce hydrogen and oxygen. This emerging technology could provide storage for surplus energy generated by intermittent renewable sources, such as wind and solar farms, allowing this energy to be used during periods of low production.

Table II.1: Characteristics of the Different Fuel Cell Types

Type	Electrolyte	Mobile Ion	Operating Temp.	Applications
PEM	Polymer Membrane	H^+ (Proton)	60 – 100 °C	Portable, Automotive, Backup Power
DMFC	Polymer Membrane	H^+ (Proton)	60 – 90 °C	Portable electronics (Laptops, Chargers)
AFC	Potassium Hydroxide (KOH)	OH^-	60 – 120 °C	Space missions, Military, Niche portable
PAFC	Phosphoric Acid	H^+ (Proton)	150 – 220 °C	Stationary (Hotels, Hospitals), CHP
MCFC	Molten Carbonate	CO_3^{-2}	600 – 700 °C	Large-scale stationary, Industrial CHP
SOFC	Solid Ceramic (Yttria-Stabilized Zirconia)	O^{-2}	500 – 1000 °C	Stationary, Auxiliary Power Units (APU)

II.6 Hydrogen Production

II.6.1 Steam Methane Reforming (SMR)

Steam Methane Reforming (SMR) typically consists of four main stages (Fig II.9):

(1) Desulfurization: Hydrogen sulfide and other sulfur compounds are removed to prevent catalyst poisoning;

(2) Pre-reforming: This step is utilized to protect against carbon formation (coking) during the primary reforming stage and to reduce the overall steam-to-carbon ratio requirement;

(3) Primary Reforming: Steam and heat are supplied to allow the reaction to proceed over a nickel catalyst at temperatures between 700°C and 830°C;

(4) Secondary Reforming: A secondary reformer utilizes air to generate heat through combustion reactions, raising the temperature to 1300°C and converting most of the remaining methane into syngas (synthesis gas).

$$CH_4 + H_2O \longrightarrow CO + 3H_2$$

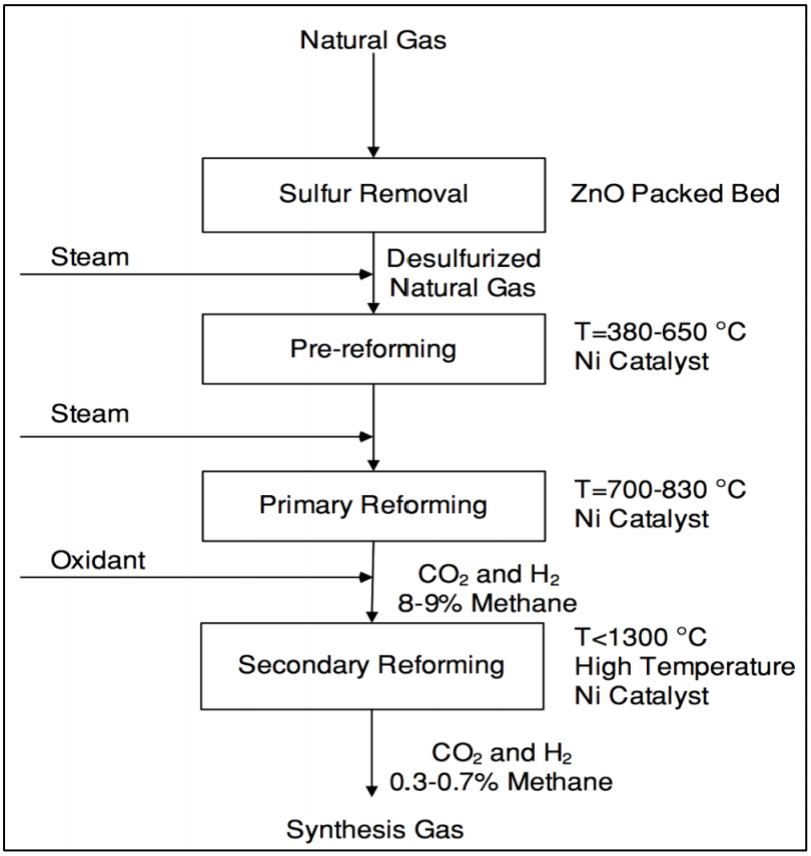


Fig II.9 Steam Methane Reforming (SMR)

II.6.2 Hydrogen Production and Storage

II.6.2.1 Hydrogen Production

Hydrogen gas (H_2) does not exist in its pure state on Earth; however, the hydrogen atom is always combined with other elements, primarily:

- Oxygen atoms, such as in water (H_2O),
- Carbon atoms, such as in methane (CH_4),
- Nitrogen atoms, such as in ammonia **(**NH_3),

Today, the majority of hydrogen is produced from fossil fuels (coal and oil), natural gas (primarily composed of methane), and biomass (plant residues and dedicated energy crops), though a portion is also generated from water.

There are three primary processes for hydrogen production, each characterized by a specific hydrogen source, distinct energy requirements, and the emission of specific byproducts.

a. Steam Reforming

The most common process for hydrogen production is the reforming of hydrocarbons (the conversion of molecules through chemical reactions) using superheated steam.

Hydrocarbons are organic compounds containing carbon and hydrogen (C_nH_m). n the presence of steam and heat, the carbon atoms (C) of the hydrocarbons dissociate. Following two successive reactions, they recombine separately to yield dihydrogen (H_2) on one side and carbon dioxide (CO_2).

$$C_nH_m + 2n.H_2O \longrightarrow (m/2 + 2n)\ H_2 + n.CO_2$$

Exemple

$$CH4 + H2O \longrightarrow CO + 3\ H\ 2$$
$$CO + H2O \longrightarrow CO\ 2 + H\ 2$$

b. Coal Gasification (and Biomass)

Coal gasification is a thermochemical process that converts waste materials (such as wood and crop residues), primarily composed of carbon and water. When heated in a reactor at very high temperatures (between 1,200 and 1,500 °C), the wood releases gases that dissociate and recombine to yield dihydrogen (H_2) and carbon monoxide (CO) on the other.

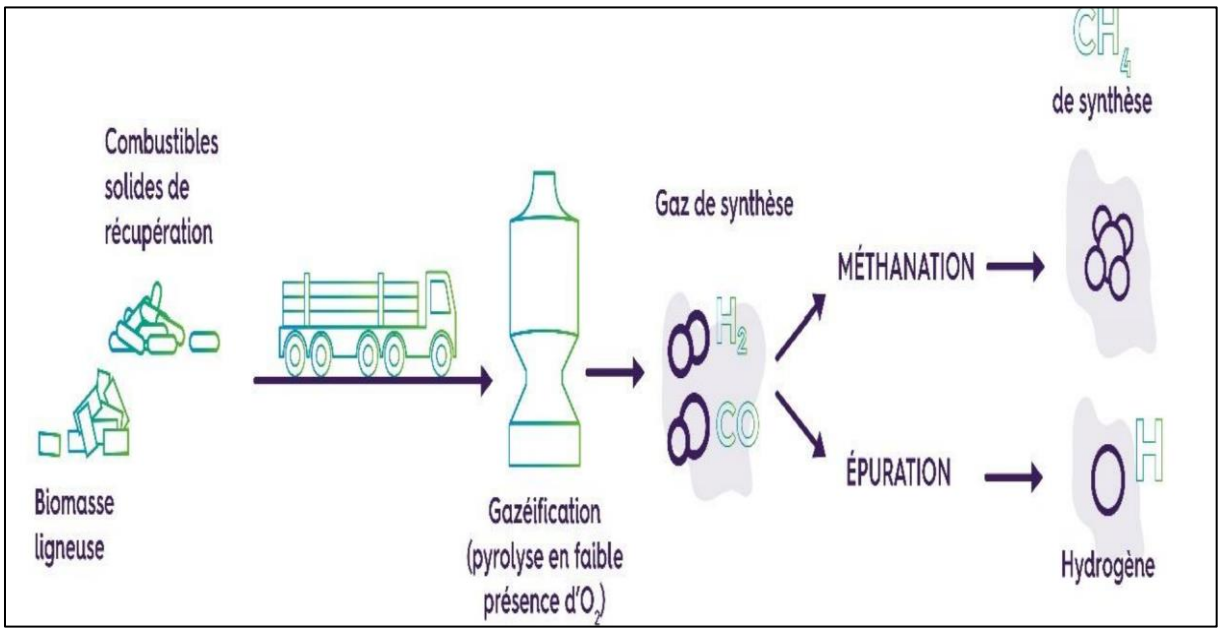


Fig II.10 Hydrogen Production via Gasification.

In the ideal case, all pyrolysis gases (pyrolysis being defined as the thermal decomposition of organic matter in the absence of oxygen) are converted into carbon dioxide and steam during partial oxidation.

If oxygen is absent, the gasification process can be summarized by two primary heterogeneous endothermic reactions:

- Steam Gasification : $C + H_2O \longrightarrow CO + H_2$
- Carbon Dioxide Gasification (Boudouard Reaction) : $C + CO_2 \longrightarrow 2CO$

c. Water Electrolysis

Producing hydrogen through electrolysis involves decomposing water molecules (H_2O) into dioxygen (O_2) and dihydrogen (H_2) using an electric current. Today, this is the most widely promoted solution for producing carbon-free (decarbonized) hydrogen.

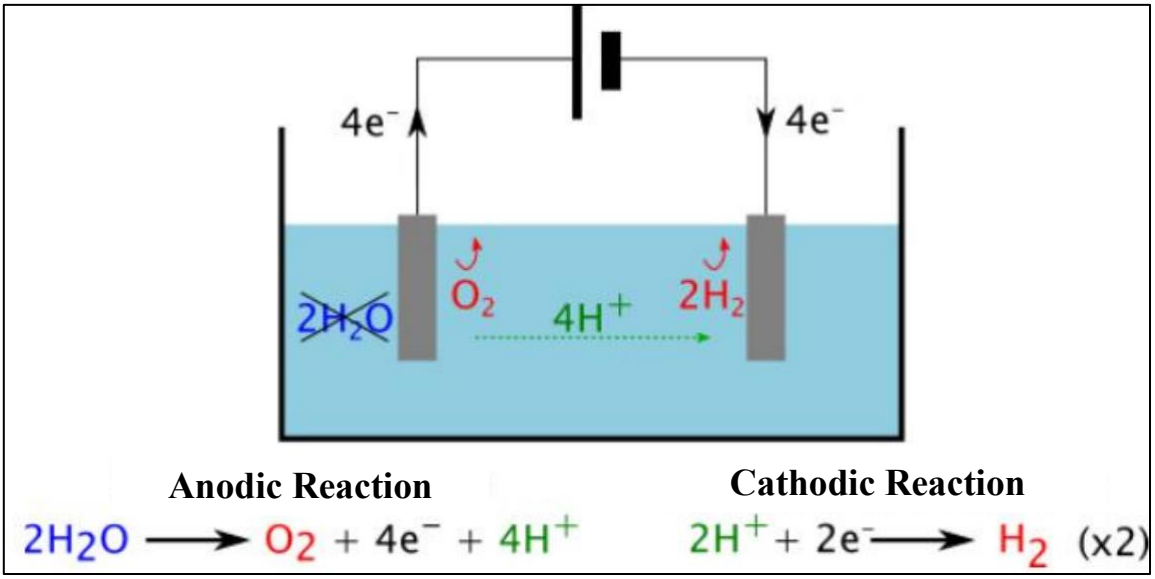


Fig II.11 Hydrogen Production via Electrolysis

II.7 Hydrogen Storage

Hydrogen storage is a critical component in the development and commercialization of fuel cell technologies. To date, hydrogen storage applications for transportation have been the primary focus for governments and companies aiming to bring this technology to market.

The performance characteristics of hydrogen storage solutions are defined by their volumetric (kWh/L) and gravimetric (kWh/kg) energy densities, cost, refueling time, discharge kinetics, and cycle life.

Several technologies and solutions exist for hydrogen storage:

- Compressed Hydrogen Storage
- Hydrogen Liquefaction and Storage
- Metal Hydrides
- Complex Hydrides
- Carbon-based Storage
- Compressed Gas Hydrogen Storage,

Since hydrogen is a lightweight and high-volume gas, it must be compressed and stored in a concentrated state to achieve a high volumetric energy density comparable to other common fuels.

For power generation applications, high-pressure storage in steel or composite tanks is likely the preferred method. Operating pressures ranging from 350 to 700 bar are currently standard**.**

Note:

As hydrogen is highly volatile and flammable, preventing all leaks is absolutely critical. Furthermore, storage tanks must be shock-resistant particularly for mobile applications-as explosions involving high-pressure vessels pose severe dangers. Additionally, the compression of hydrogen is an energy-intensive process that requires both power input and a dedicated cooling system.

- **Liquid Hydrogen Storage**

Storing hydrogen in liquid form is certainly an attractive solution, as it contains nearly 800 times more energy per unit volume in its liquid state at -253°C than in its gaseous state at 0°C and ambient pressure. However, it is challenging to implement because hydrogen liquefies at approximately -253°C (it is the second gas after helium to liquefy at such an extremely low temperature).

The storage tank typically features a double-walled structure with a vacuum or insulating materials between the layers to minimize thermal losses through convection.Stockage dans des hydrures métalliques

Certain metals (pure or alloyed) absorb hydrogen within their structure. The metallic compound (e.g., magnesium) acts as a 'hydrogen sponge'.

In metal hydrides, hydrogen is stored in its atomic form (H) rather than its molecular form (H_2), as is the case in traditional storage tanks.

Metal hydrides offer the potential to store large quantities of hydrogen at relatively low pressures and volumes. In fact, the storage density of metal hydrides can even exceed that of liquid hydrogen storage.

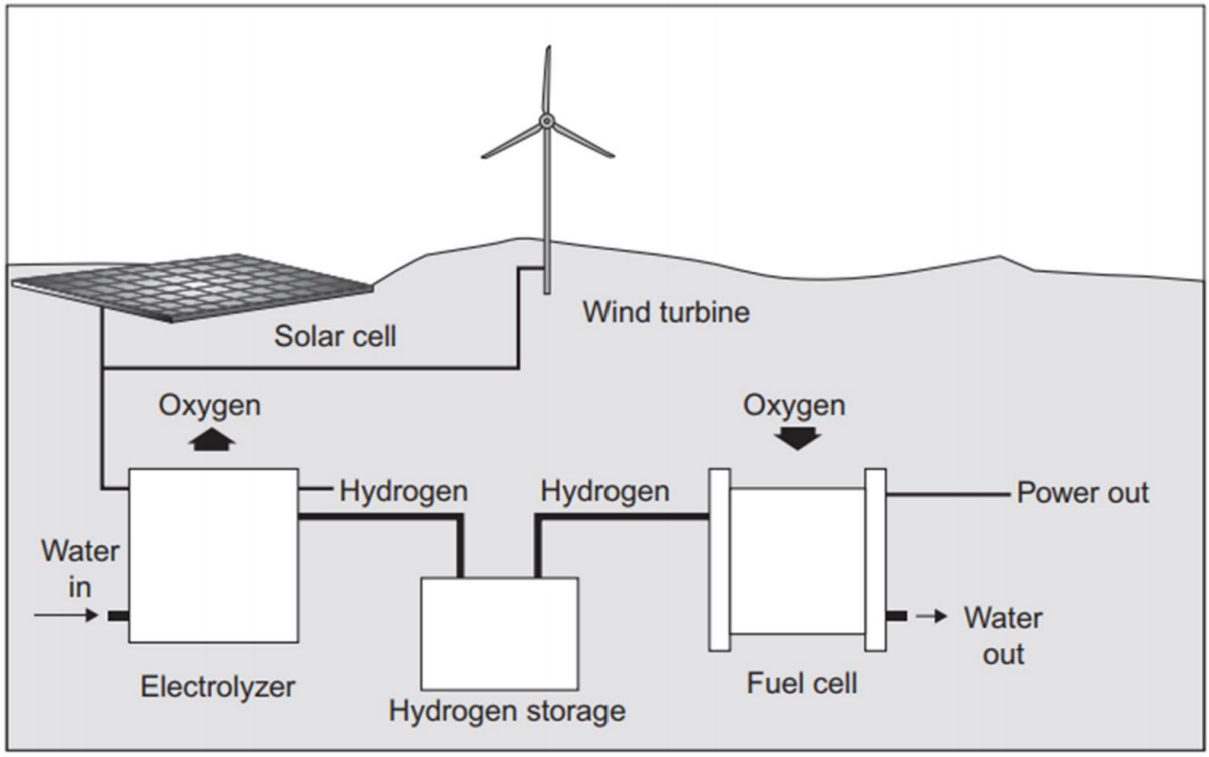


Fig II.12: Simple hydrogen energy production and storage system.

II.8 Applications in the Automotive Sector

Fuel Cell Vehicles (Fig. II.13), or FCEVs (Fuel Cell Electric Vehicles), share most of their components with Internal Combustion Engine (ICE) vehicles and are quite similar to Battery Electric Vehicles (BEVs). The distinctive systems are the fuel cell stack, its associated control system, and the hydrogen storage or fuel conversion systems.

PEM fuel cells possess a range of characteristics that make them well-suited for mobile applications. They offer fast start-up from ambient temperature, adequate power-to-volume and power-to-weight ratios, as well as a high capacity for load-following. However, they require both highly active catalysts and high-purity fuel with only trace levels of contaminants.

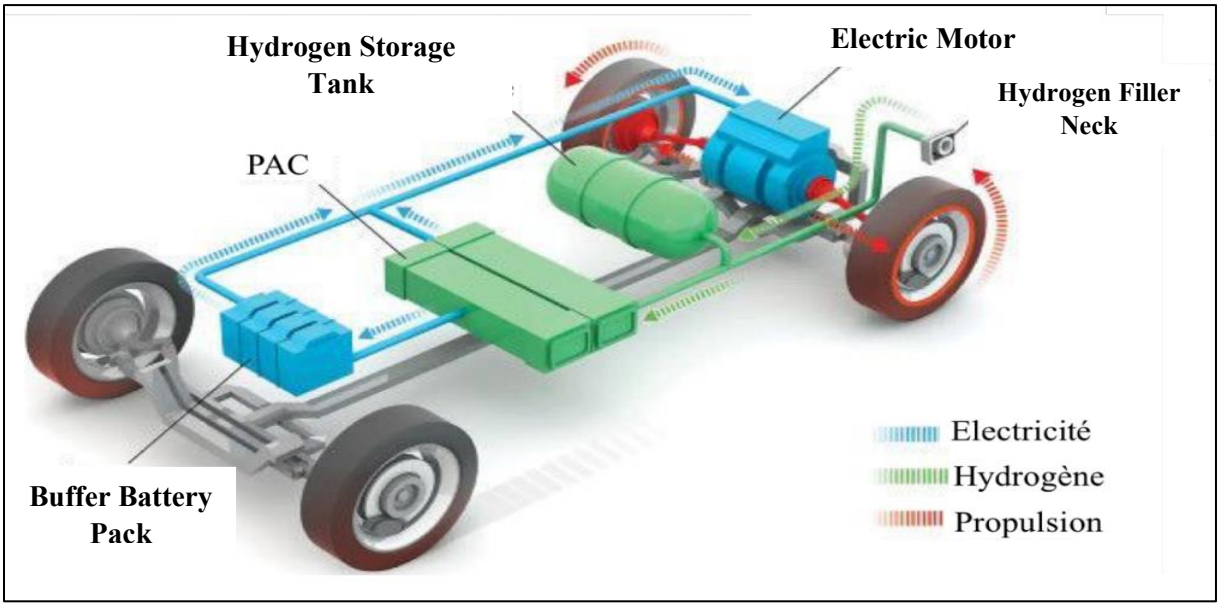


Fig II.13 Operating Principle of an Electric Vehicle

Automotive applications are currently benefiting from extensive Research and Development (R&D) efforts. Indeed, car manufacturers are allocating a significant portion of their budgets to integrating fuel cells into vehicles for both urban and individual transportation.

A series of PEMFC-powered cars has been developed by Daimler-Benz since 1994, in collaboration with Ballard. In 1997, Daimler-Benz launched a methanol-powered vehicle with a driving range of 640 km, the first of its kind

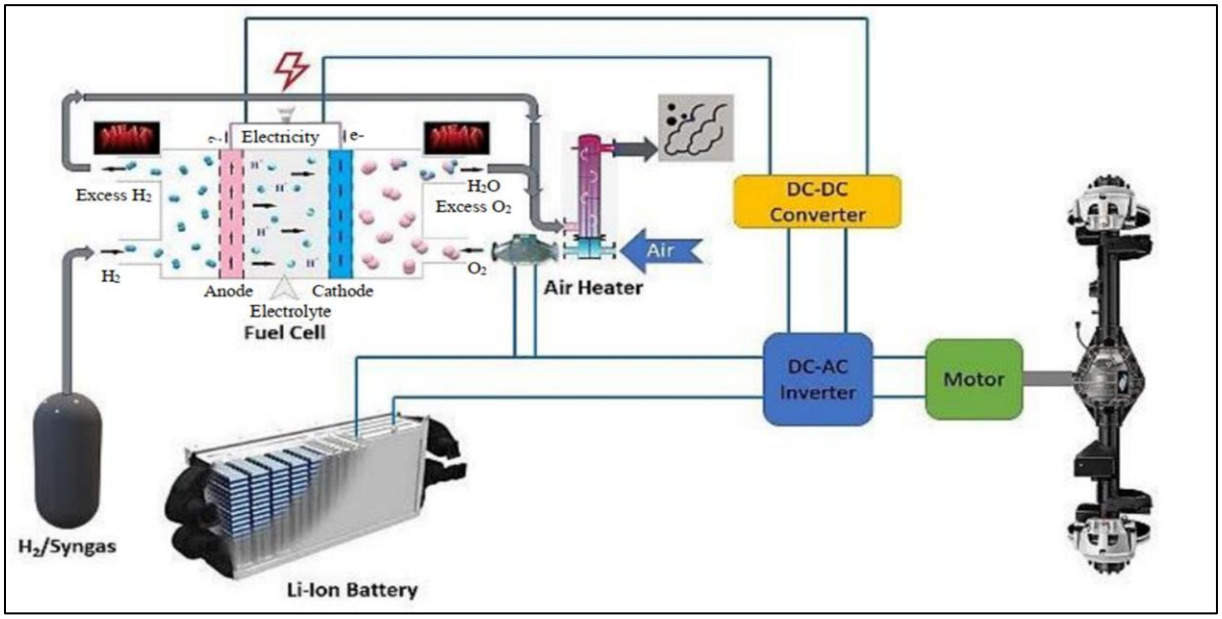


Fig II.14: Fuel cell system for an Electric Vehicle (FCEV).

II.9 Residential Applications

The application of fuel cells in the residential sector is a key strategic move. Residential heating and power supply account for approximately one-quarter of global energy consumption and carbon emissions.

Two critical factors govern fuel cell-based Combined Heat and Power (CHP) systems: the electrical and thermal energy demands. Residential fuel cell systems typically have an electrical capacity ranging from 0.7 to 1.5 kW. This capacity is sufficient to cover the entire electricity demand and approximately half of the thermal demand of a household, with the remainder being supplied by an integrated boiler and a heat storage tank.

Practical challenges arise from the system's size and weight, which often lead to outdoor installations. However, smaller and more compact models are currently under development.

II.10 Applications in Renewable Energy Systems (RES)

Renewable energy sources, such as solar and wind power, are intermittent by nature. The capacity factor—defined as the ratio of the average power output over a given period to the maximum or nominal power—is approximately 20% for solar installations and around 30% for wind farms.

A fuel cell system (coupled with an electrolyzer) can be used to store surplus energy when renewable sources are available by converting electricity into hydrogen. This hydrogen is then used to generate electricity when these renewable sources are unavailable.

Hydrogen can also be used as a fuel for cooking, heating, or transportation. In such cases, the electrolyzer and the renewable energy source must be sized accordingly to meet these specific demands.

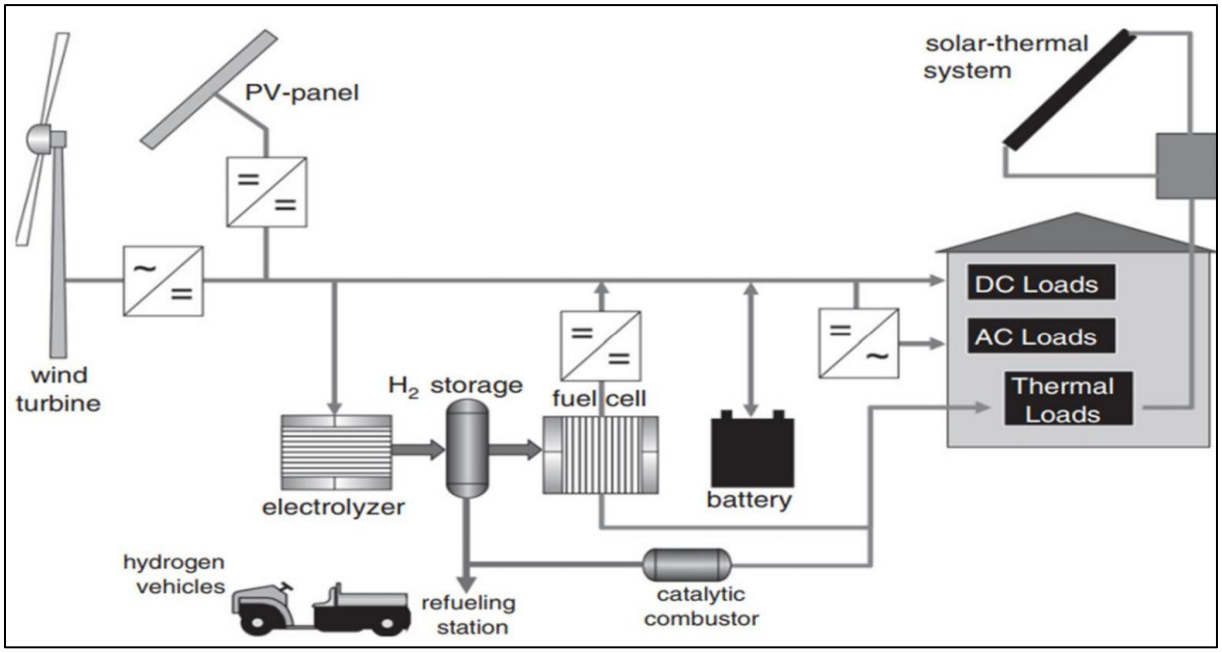


Fig II.15: Regenerative Fuel Cell (RFC) within a standalone Renewable Energy System (RES).

Such a system would ensure energy independence for an appliance, a household, a farm, or a community in a remote region. This technology also holds great potential for developing countries, where energy and electricity demands are relatively low and the existing electrical infrastructure is either insufficient or non-existent.

II.11 Conclusion

The technical analysis of fuel cell (FC) technology presented in this chapter underscores its role as a pivotal electrochemical energy converter, bridging the gap between intermittent renewable generation and reliable end-user applications. Unlike thermal combustion, the fuel cell operates on direct chemical-to-electrical energy conversion, governed by the Gibbs free energy potential, which inherently allows for higher theoretical efficiencies and zero-carbon local emissions.

The study reveals that the "one-size-fits-all" approach does not apply to fuel cells. Each variant is engineered for a specific niche dictated by its electrolyte and operating temperature:

- **PEMFCs and DMFCs** dominate the portable and automotive sectors due to their low-temperature operation, fast start-up, and high-power density.
- **High-temperature cells (MCFC and SOFC)** are optimized for stationary power plants, where their ability to perform internal reforming of hydrocarbons and integrate with gas turbines allows for combined electrical efficiencies reaching up to 75%.

A critical takeaway is that the viability of fuel cells is inextricably linked to the hydrogen value chain. While Steam Methane Reforming (SMR) is currently the industrial standard for production, it remains carbon-intensive. The transition to Water Electrolysis powered by renewables is the essential pathway toward "green" hydrogen. Furthermore, overcoming the volumetric energy density constraints of hydrogen—whether through high-pressure compression, cryogenic liquefaction, or advanced metal hydrides—remains the primary engineering hurdle for widespread commercialization.

Beyond individual vehicles or buildings, the true potential of this technology lies in systemic integration. The use of Regenerative or Reversible Fuel Cells (URFC) offers a circular energy solution, acting as a long-term storage medium for surplus wind and solar energy. In residential contexts, Combined Heat and Power (CHP) systems maximize the second law of thermodynamics by utilizing byproduct heat, achieving overall energy utilization rates of up to 90%.

Fuel cell technology represents a mature yet evolving field. The challenge for the future Master of Engineering lies in optimizing the Faradaic and voltage efficiencies of these systems while developing a cost-effective infrastructure for hydrogen storage and distribution to ensure global energy resilience.

CHAPTER III

Electrochemical Energy Storage

III.1 Introduction

This section presents two primary forms of energy storage: electrochemical storage, through various battery technologies, and electrical storage, utilizing capacitors and supercapacitors (ultracapacitors).

III.2 Solar Storage Batteries

Solar photovoltaic (PV) batteries operate similarly to any rechargeable battery; they store direct current (DC) from an external source (e.g., photovoltaic panels) and discharge DC power whenever energy is required.

III.2.1 Connection of Solar Batteries to PV Systems

here are two primary methods for integrating a battery storage system into a PV system:

1- DC-Coupling (PV-side installation): The batteries are installed alongside the solar inverter on the PV panel side (Fig. III.1). They are charged directly from the panels, and the current is only converted into alternating current (AC) when it is consumed.

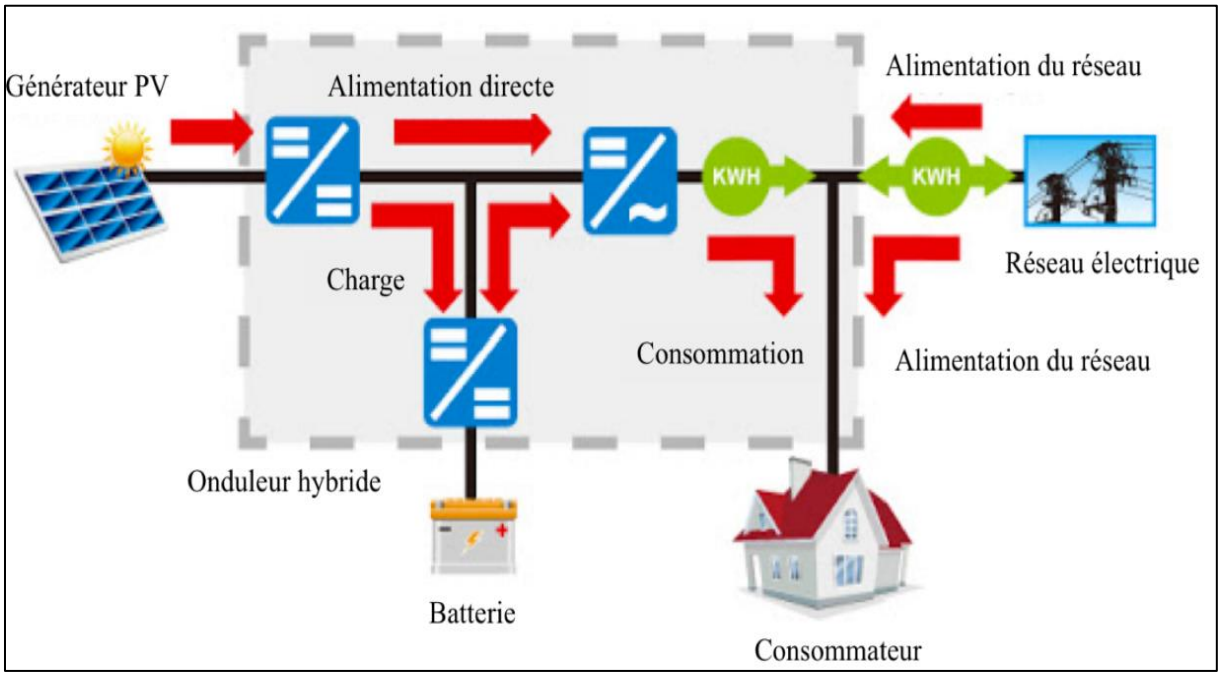


Fig III.1 DC-Coupled Battery Storage System (PV-side installation)

2- AC-Coupling (Grid-side installation): The batteries are installed on the grid side (Fig. III.2), where the DC power from the PV has already been converted into AC. A separate battery inverter converts the AC back into DC for storage. During discharge, this same dedicated inverter reconverts the stored DC back into AC for consumption.

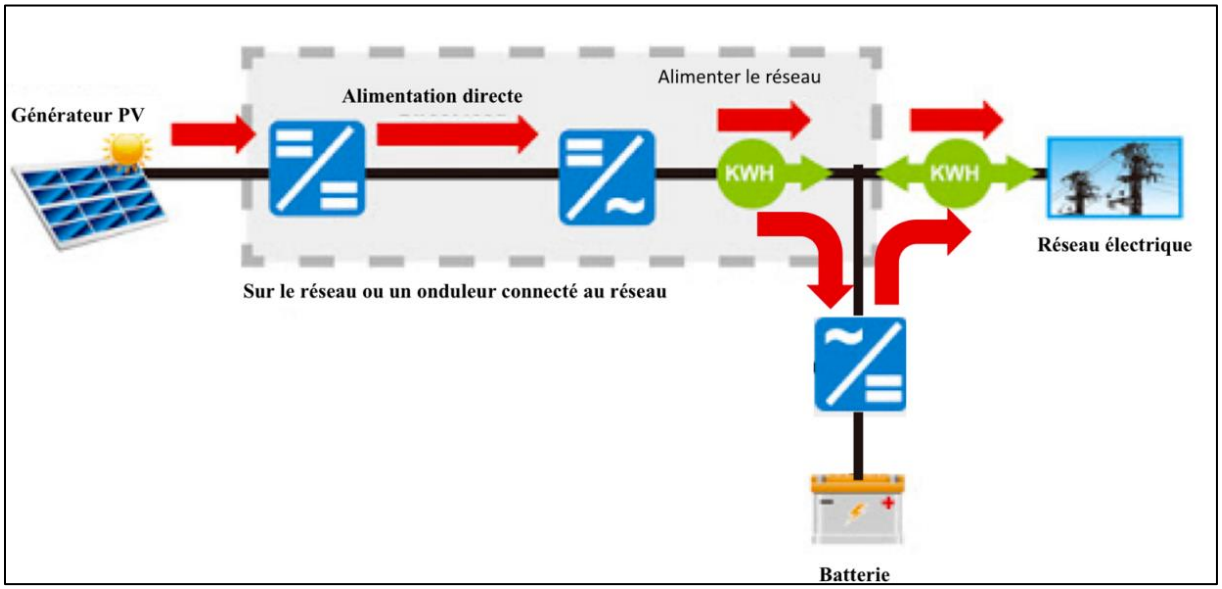


Fig III.2. AC-Coupled Battery Storage System (Grid-side installation).

III.2.2 Types of Solar Batteries

The battery types commonly used in photovoltaic (PV) systems include: Lead-acid batteries, Nickel-metal hydride (NiMH) batteries, Nickel-cadmium (NiCd) batteries, and Lithium-ion batteries (LIB).

III.2.2.1 Lead-Acid Batteries

This is the oldest and most mature technology available. Sealed batteries (VRLA) are spill-proof and do not require periodic maintenance. Flooded lead-acid batteries (Fig. III.3) are generally the most cost-effective option but require the addition of distilled water at least once a month to replenish the water lost during the normal charging process.

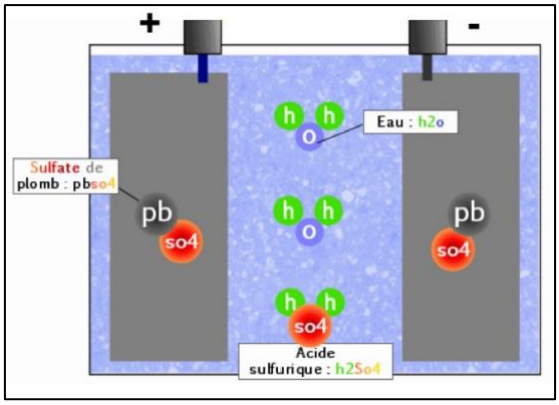


Fig III.3 Lead-Acid Batteries

III.2.2.2 Nickel-Metal Hydride Batteries (NiMH)

NiMH batteries exhibit high energy density, comparable to that of lithium-ion batteries (see below). However, NiMH batteries suffer from a high self-discharge rate.

III.2.2.3 Nickel-Cadmium Batteries (NiCd)

NiCd batteries (Fig. III.4) exhibit a significantly lower energy density than lithium-ion batteries. Furthermore, NiCd batteries suffer from the memory effect: they lose their usable energy capacity if they are repeatedly recharged after being only partially discharged. This memory effect impairs both performance and cycle life when the batteries are recharged before reaching a full state of discharge**.**

These drawbacks render NiMH and NiCd batteries unsuitable for photovoltaic (PV) storage systems.

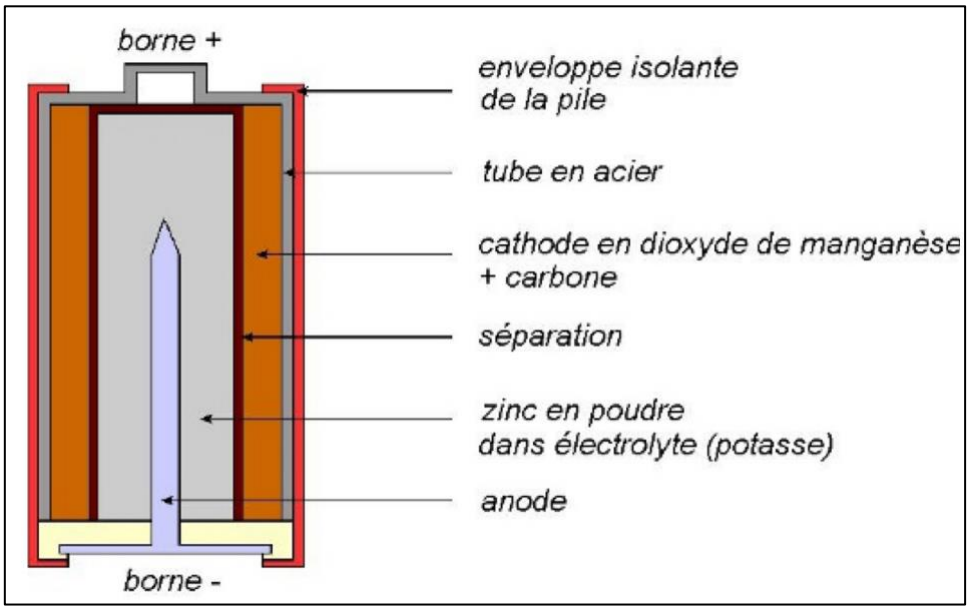


Fig III.4 Nickel-Cadmium Batteries (NiCd).

III.2.2.4 Lithium-ion Batteries (LIB)

Lithium-ion batteries (LIB) and lithium-ion polymer batteries (LiPo) have been the subject of extensive research in recent years. Their high energy density has made them the preferred technology for lightweight storage applications, such as mobile phones.

However, these technologies still face challenges regarding high costs and a lack of technological maturity in certain large-scale applications.

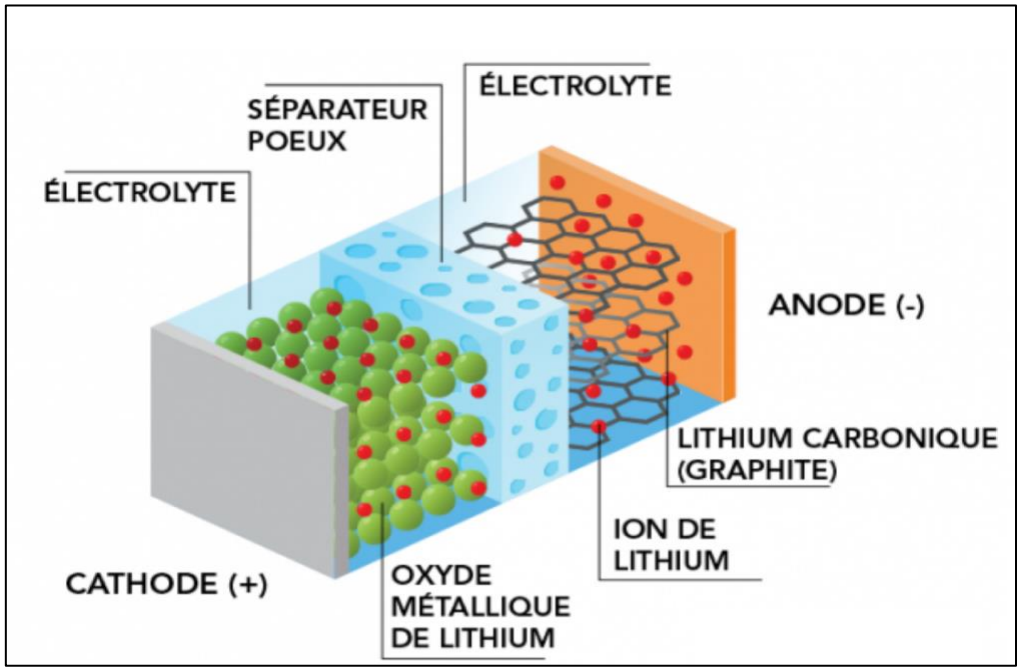


Fig III.5 Lithium-ion Batteries (LIB)

III.3 Battery Technology (Accumulators)

Accumulators, or battery packs, consist of at least two voltaic cells connected in series to provide a constant DC voltage at the battery's output terminals. This voltage is generated by a chemical reaction within the cell. The electrodes are immersed in an electrolyte, which forces the electrical charge to separate into ions and free electrons.

III.3.1 Operating Principle

A battery operates through oxidation and reduction reactions between an electrolyte and metallic electrodes. When two dissimilar metallic substances (electrodes) are placed in a diluted electrolyte, oxidation and reduction reactions occur at the respective electrodes.

As a result of the oxidation reaction, one electrode becomes negatively charged (the Anode in discharge mode), while due to the reduction reaction, the other electrode becomes

positively charged (the Cathode). Thus, the cathode forms the positive terminal, while the anode forms the negative terminal of the battery.

Understanding the fundamental principle of a battery requires a basic grasp of electrolytes and electron affinity. In essence, when two different metals are immersed in an electrolyte, a potential difference is created between them based on their relative electrochemical potentials.

III.3.2 Electrical Parameters of Accumulators

III.3.2.1 Voltage

Voltage is the potential difference across the battery terminals, expressed in Volts (V). The voltage indicated on a battery is its nominal voltage; however, the Open Circuit Voltage (OCV) of a fully charged battery is typically 5% to 7% higher than its nominal value.

The closed-circuit voltage represents the operating voltage. It is essential to always verify the correct nominal voltage before connecting a battery.

III.3.2.2 Capacity

Battery capacity is a measure of the charge stored by the battery (typically expressed in Ampere-hours, Ah) and is determined by the mass of the active material within the cells.

Capacity represents the maximum amount of energy that can be extracted from the battery under specific conditions. However, actual capacity can vary significantly from the nominal rating, as it depends heavily on the battery's age and history, charge and discharge rates (C-rate), and operating temperature.

For example, a 1 Ah capacity battery can theoretically supply a 1 A current for one hour, 0.1 A for 10 hours, or 0.01 A (10 mA) for 100 hours.

III.3.2.3 Energy Density

Energy density, also referred to as specific energy or gravimetric energy density, defines the battery capacity per unit of mass (Wh/kg). Conversely, volumetric energy density reflects the capacity per unit of volume, typically expressed in Watt-hours per liter (Wh/L).

III.3.2.4 Charging Methods

There are three common modes for charging a battery: constant voltage, constant current, and a combination of constant voltage/constant current, with or without an intelligent charging circuit.

Constant Voltage (CV) allows the full output current of the charger to flow into the battery until the power supply reaches a preset voltage level. The current then decreases to a minimum value once this voltage threshold is attained. The battery can remain connected to the charger until needed, staying at a **'float voltage'**—a trickle charge used to compensate for the battery's normal self-discharge.

Constant Current (CC) is a simple charging method where the current intensity is set to approximately 10% of the battery's maximum capacity **(C/10 rate). The** charging time is relatively long, with the drawback that the battery may overheat if overcharged, leading to premature failure. This mode is suitable for Ni-MH batteries, which must be disconnected once fully charged.

Constant Current / Constant Voltage (CC/CV) is a combination of the two aforementioned methods. The charger limits the current intensity to a predefined level until the battery reaches a specific voltage threshold. Subsequently, the current tapers off until the battery is fully charged. Lead-acid batteries typically utilize this CC/CV charging profile.

III.3.2.5 Discharge

If an accumulator remains connected to a discharge circuit for too long, it will undergo deep discharge. Consequently, it will shut down, and the internal electrochemical exchange system will be deactivated (rendered non-functional).

III.3.2.6 Self-Discharge

The capacity loss rate (per month) varies depending on the battery technology: Lead-acid 5%, Lithium-ion 10%, Ni-Cd 20%, and Ni-MH 30%. Self-discharge is typically higher during the first 24 hours and decreases thereafter. Furthermore, the self-discharge rate increases with the battery's age and the ambient temperature.

III.3.2.7 Depth of Discharge (DoD)

A battery must not be discharged below a specific threshold; otherwise, it faces the risk of permanent damage.

III.3.3 Characteristics of a Lead-Acid Accumulator

III.3.3.1 Discharge

In a discharged state, both the positive and negative terminals are converted into lead sulfate ($PbSO_4$) while the electrolyte loses a significant portion of its dissolved sulfuric acid and becomes primarily water. The discharge process is driven by the substantial reduction in energy that occurs when the acid's hydrated protons $2H^+$ react with the O^{2-} ions from PbO_2 to form the strong O-H bonds in water H_2O.

Negative Terminal Reaction (Anodic Reaction)

$$Pb + HSO^-_4 \longrightarrow PbSO_4 + H^+ + 2e^-$$

The release of two conducting electrons gives the lead electrode a negative charge (Fig. III.6).

As these electrons accumulate, they generate an electric field that attracts hydrogen ions (H^+) and repels sulfate ions (HSO_4^-), leading to the formation of an electric double layer near the surface. The hydrogen ions screen the charged electrode from the solution, which limits further reaction unless the charge can flow out of the electrode.

Positive Terminal Reaction (Cathodic Reaction)

Exploiting the metallic conductivity of lead dioxide PbO_2.

$$PbO_2 + HSO^-_4 + 3H^+ + 2e^- \longrightarrow PbSO_4 + 2H_2O$$

III.3.3.2 Charging

In a fully charged state, the negative plate consists of lead (Pb), while the positive plate consists of lead dioxide (PbO^2). The electrolyte solution contains a higher concentration of aqueous sulfuric acid (H_2SO_4), which stores the majority of the chemical energy.

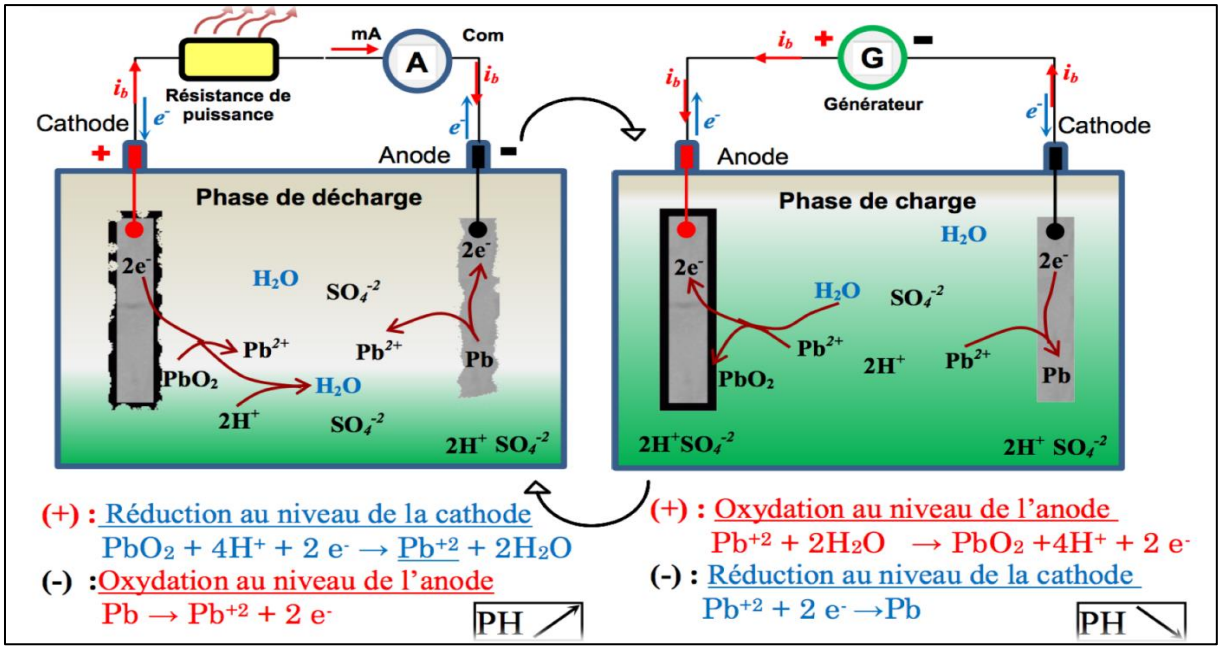


Fig III.6 Operating principle of a lead-acid battery.

III.4. Supercapacitors (Ultracapacitors)

III.4.1 Overview of Capacitors

A capacitor consists of two conductors (metallic plates) placed near each other without making direct contact (Fig. III.7). These metallic plates are known as the capacitor electrodes (or armatures). They are separated by an insulating material of varying thickness called a dielectric**.**

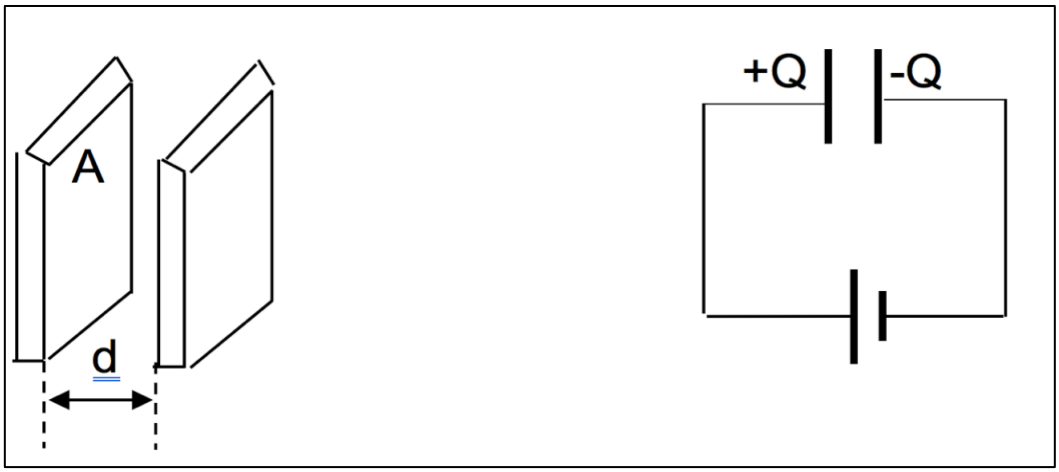
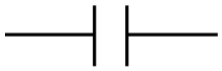


Fig III.7 Capacitor

When a voltage is applied across the electrodes of a capacitor, it charges rapidly. The electrode connected to the positive terminal of the battery carries a charge of +Q, while the one connected to the negative terminal carries an equal and opposite charge of -Q.

In electrical schematics, capacitors are represented by the following symbol:



III.4.1.1 Capacitance of a Capacitor

The capacitance of a parallel-plate capacitor is directly proportional to the surface area (A) of the smaller of the two plates (expressed in m^2) and inversely proportional to the distance or separation (d) between these two conductive plates (i.e., the thickness of the dielectric), expressed in meters.

The generalized equation for the capacitance of a parallel-plate capacitor is given as follows:

$$C = \varepsilon (A / d)$$

Where ε represents the absolute permittivity of the dielectric material.

The permittivity of a vacuum has a constant value of 8,84 x 10^{-12} Farads per meter. Capacitance is the electrical property of a capacitor and is a measure of its ability to store an electric charge on its two plates. The unit of capacitance is the Farad (abbreviated as F), named after the British physicist Michael Faraday.

A capacitor is defined as having a capacitance of one Farad when a charge of one Coulomb is stored on its plates by a voltage of one Volt. Capacitance is always a positive value and has no negative units. However, the Farad is an extremely large unit of measurement to be used on its own; therefore, submultiples of the Farad are generally used, such as micro-Farads, Nano-Farads and pico-Farads.

III.4.1.2 Role of the Dielectric in a Capacitor

Dielectrics prevent charges from passing from one electrode to the other, which would otherwise discharge the capacitor. Furthermore, the presence of a dielectric allows the electrodes to be positioned closer together without the risk of physical contact, thereby significantly increasing the capacitance**.**

III.4.1.3 Capacitors in Series and Parallel

Capacitors can be connected in two primary configurations to achieve specific capacitance or voltage requirements.

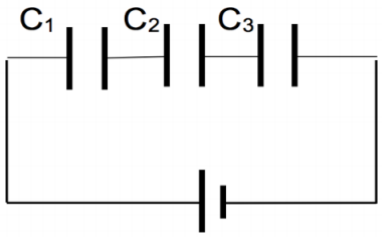


Fig III.8 Series connection of capacitors.

As shown in Fig. III.8, the total voltage is the sum of the voltages across each individual capacitor.

$$V= V_1 + V_2 + V_3 \; ; \; V= Q/C$$

By substituting the voltages with their respective values, we obtain:

$$Q/C= Q_1/C_1 + Q_2/C_2 + Q_3/C_3$$

The equivalent capacitance of capacitors connected in series is given by:

$$1/C = 1/C_1 + 1/C_2 + 1/C_3$$

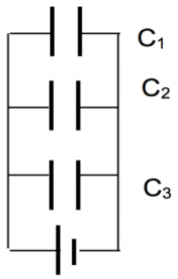


Fig III.9 Parallel connection of capacitors**.**

$$V= V_1= V_2 = V_3$$

$$Q= Q_1 = Q_2 = Q_3$$

$$C.V = C_1.V = C_2.V = C_3.V$$

Based on the previous equations, the equivalent capacitance of capacitors connected in parallel is given by:

$$C = C_1 + C_2 + C_3$$

The electrical energy stored in a capacitor is given by the following equation:

$$E = \frac{Q^2}{2C} = \frac{1}{2}QV = \frac{1}{2}C.V^2$$

III.4.2 Overview of Supercapacitors

Similar to a conventional capacitor, a supercapacitor consists of two plates separated by an electrolyte-based interface (Fig III.10). A supercapacitor differs from an ordinary capacitor in two critical ways: its plates have a significantly larger surface area, and the distance between them is much smaller. This is because the separator between the two plates operates differently than a conventional dielectric.

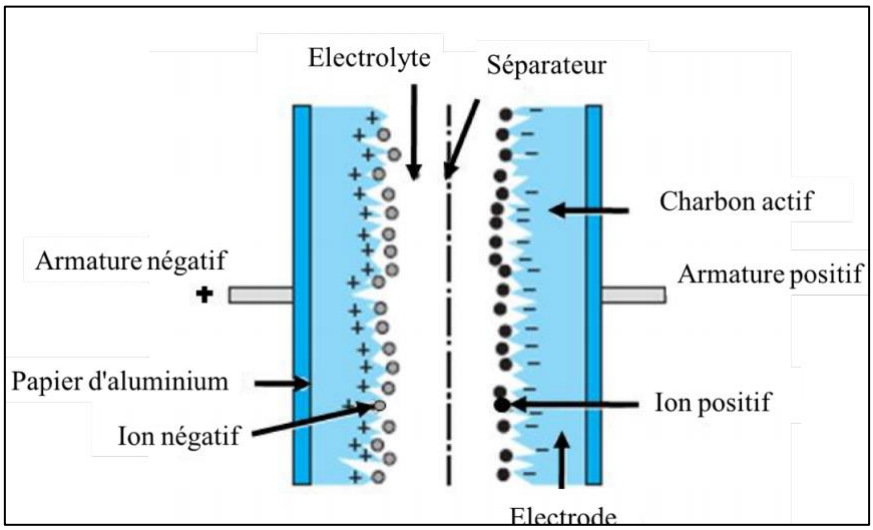


Fig III.10 Internal structure and operating principle of a supercapacitor**.**

The plates are made of a metal coated with a porous substance such as powdered activated carbon, which provides a significantly larger surface area to store much more charge.

In an ordinary capacitor, the plates are separated by a relatively thick dielectric, such as mica (a ceramic), a thin plastic film, or even simply air (as seen in certain devices like radio tuning dials). When a capacitor is charged, positive charges accumulate on one plate and negative charges on the other, creating an electric field between them. This field polarizes the dielectric, causing its molecules to align in the opposite direction of the field, thereby

reducing its overall strength. This phenomenon allows the plates to store more charge at a given voltage.

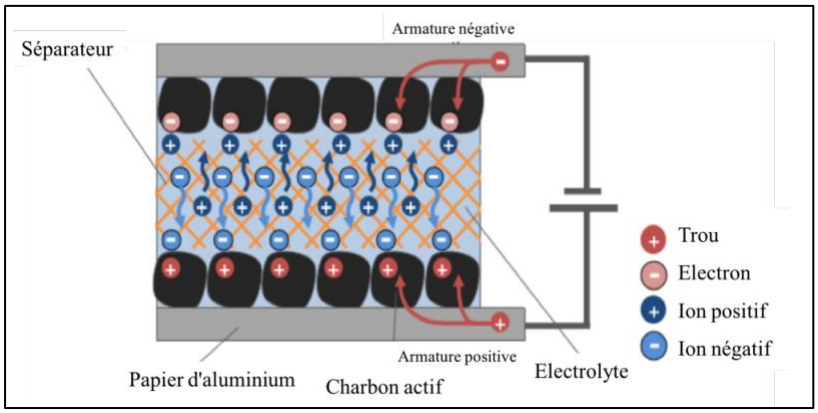


Fig III.11 Operating principle of a supercapacitor (Electric Double-Layer Capacitor).

In a supercapacitor (Fig. III.11), there is no conventional dielectric. Instead, the two plates are immersed in an electrolyte and separated by a very thin insulator (which may be made of carbon, paper, or plastic). When the plates are charged, an opposite charge forms on each side of the separator, creating an electric double layer (EDL) of extreme thinness—potentially as thin as a single molecule. This is significantly thinner than a conventional dielectric, whose thickness can range from a few microns to a millimeter or more. Consequently, supercapacitors are frequently referred to as double-layer capacitors, or more specifically, Electric Double-Layer Capacitors (EDLC).

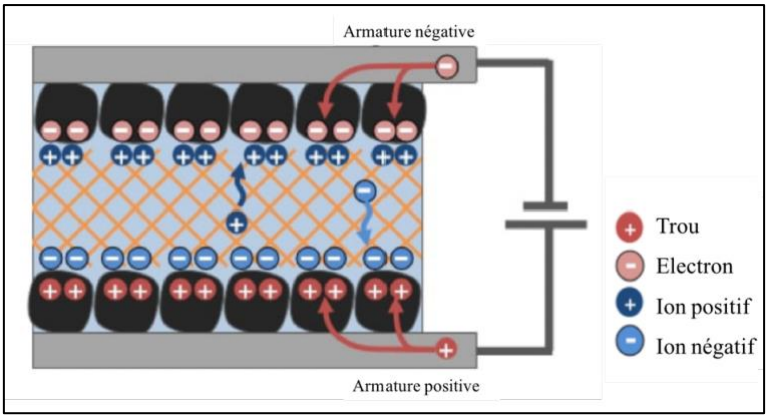


Fig III.12 A charged supercapacitor (Electric Double-Layer).

The capacitance of a capacitor increases as the surface area of the plates expands and the distance between them decreases. Consequently, supercapacitors achieve a significantly higher capacitance through a combination of a larger effective surface area (due to their activated carbon construction) and a reduced separation distance (thanks to the highly

efficient electric double-layer). Fig. III.12 illustrates a charged supercapacitor in its steady state (idle state).

III.4.3 Applications of Supercapacitors

Today, small-scale supercapacitors are widely used as maintenance-free power sources for integrated memories and microcomputers. Among the new applications proposed for large-scale supercapacitors are load leveling in electric and hybrid vehicles, as well as in the traction sector, engine starting, telecommunications, and energy quality and reliability requirements for uninterruptible power supply (UPS) systems.

In general, supercapacitors can be categorized into the following two application areas:

1. High-Power Applications: Due to their high power density, supercapacitors offer new opportunities for power electronics. Any application requiring high power peaks for short durations can be supplied by these devices. Fast energy management in hybrid vehicles or the starting of heavy-duty diesel engines are typical examples where a high current is required for a short period.**

2. Low-Power Applications: In this sector, even though supercapacitors are significantly larger than conventional capacitors, they offer enough advantages to replace batteries. In this field, inverters and safety backup systems are the most representative examples.

III.4.4 Different Families of Supercapacitors

There are several classification standards for supercapacitors. This section primarily presents two classification methods. The first is based on the different energy storage mechanisms of the electrode materials, and the second is based on the types of electrolytes used.

II.4.4.1 Classification based on Energy Storage Mechanisms

Supercapacitors can be divided into three categories: symmetric supercapacitors, asymmetric supercapacitors, and hybrid supercapacitors**.**

III.4.4.2 Classification Based on Electrolyte Types

According to the type of electrolyte used, supercapacitors are divided into aqueous electrolytes and organic electrolytes. Within these, aqueous electrolytes include: acidic electrolytes, alkaline electrolytes, and neutral (or salt-based) electrolytes.

III.4.5 Modeling of Supercapacitors

A supercapacitor can be modeled in a simplified form as an RC circuit, consisting of an internal resistance and a voltage-dependent linear capacitance (Fig. III.12). This model is suitable for applications where the stored energy is of primary importance and the transient response can be neglected.

The simplified model utilizes a PLECS variable capacitor component to implement the voltage-dependent capacitance. This variable capacitor model is based on the following equation:

:

$$i = \frac{d}{dt}(C.v) = C.\frac{dv}{dt} + v\frac{dC}{dt}$$

Since the voltage and its derivative are computed, the capacitance C, and its time derivative $\frac{dC}{dt}$, are required as external inputs.

However, cannot be easily calculated. Therefore, the above equation must be rearranged using the chain rule to allow the second term to be expressed as a factor of $\frac{dv}{dt}$ rather than $\frac{dC}{dt}$

$$i = C.\frac{dv}{dt} + v\frac{dC}{dt}\frac{dv}{dt}$$
$$i = \frac{dv}{dt}\left(C + \frac{dC}{dt}\right) + 0$$
$$i = \frac{dv}{dt}C_1$$

Voltage Sensitivity Equation

$$C_1(v) = C_0 + k_v v$$

This rearrangement allows for the implementation of the variable capacitance characteristic by providing the C_1 term to the capacitance value input and setting the

capacitance derivative input to zero. Calculating C + v. Dc for the voltage-effect equation yields:

$$C_1 = C_0 + 2k_v v$$

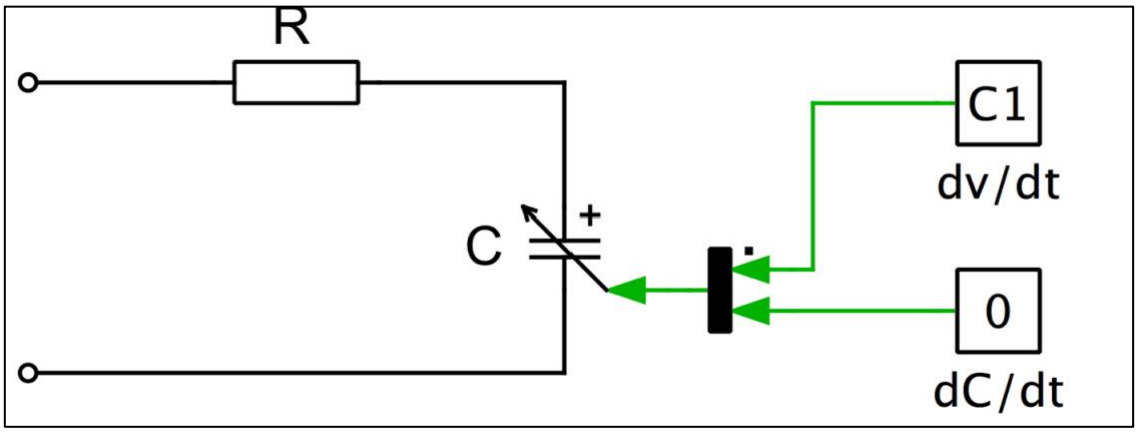


Fig III.12 Equivalent circuit model of a supercapacitor (Simplified RC Model).

III.5 Conclusion

The technical analysis of this chapter highlights a critical paradigm in modern energy management: the necessity of a bifurcated storage strategy that leverages both electrochemical accumulators and high-power electrical storage (supercapacitors) to meet the complex demands of the energy transition.

The integration of battery technologies into photovoltaic systems reveals a fundamental trade-off between maturity, cost, and energy density. While Lead-Acid batteries remain the most cost-effective and mature solution for stationary applications, the transition toward Lithium-Ion (LIB) and LiPo technologies is driven by their superior energy density, despite challenges in large-scale cost-efficiency. A Master-level understanding requires recognizing that battery performance is not static; it is a dynamic variable heavily influenced by the C-rate, Depth of Discharge (DoD), and complex charging profiles like CC/CV, which are essential for maximizing the operational life of the chemical cells.

The study of Supercapacitors (EDLC) introduces a distinct storage mechanism based on the Electric Double-Layer (EDL) rather than faradaic chemical reactions. By utilizing activated carbon to maximize surface area and minimizing separation distance to a molecular scale, these devices achieve a high-power density that batteries cannot match. This makes them indispensable for high-power applications such as regenerative braking in hybrid vehicles and peak load leveling where rapid energy bursts are required.

From a modeling perspective, the shift from a linear capacitor model to a voltage-dependent RC circuit for supercapacitors allows for precise simulation of transient responses in power electronics. Furthermore, the analysis of self-discharge rates (ranging from 5% in Lead-Acid to 30% in Ni-MH) and the memory effect in NiCd cells underscores that system reliability is dependent on matching the specific electrochemical property of a storage medium to its intended duty cycle.

The mastery of this field lies in the ability to hybridize these technologies: using batteries for high-energy bulk storage and supercapacitors for high-power transient stabilization. This synergy is the cornerstone of developing resilient, efficient, and long-lasting energy storage infrastructures for the smart grids of the future.

References

References :

[1] J. R. Bernard Multon, «Les différentes technologies stationnaires de stockage de l'électricité,» smart grids-cre, 2010.

[2] Okba Djelailia, Mounia Samira Kelaiaia, Hocine Labar, Salah Necaibia, Faycel Merad, «Energy Hybridization Photovoltaic/Diesel Generator/Pump Storage Hydroelectric Management Based on Online Optimal Fuel Consumption Per kWh, » Sustainable Cities and Society, vol. 44, pp. 1-15, 2019.

[3] B. Zoppé, C. Pellone, T. Maitre, P. Leroy, «Flow Analysis Inside a Pelton Turbine Bucket, » Journal of Turbomachinery, pp. 500-511, 2006.

[4] J.-E. P. Thierry Jacob, «Francis Turbine Surge: Discussion and Data Base, » Hydraulic Machinery and Cavitation, pp. 855-864, 1996.

[5] Dragica Jo št, Andrej Lipej, Kazimir Oberdank, Mateja Jamnik, Boris Velen šek, «Numerical Flow Analysis of a Kaplan Turbine, » Hydraulic Machinery and Cavitation, pp. 1123-1132, 1996.

[6] Shahram Khosrowpanah, A. A. Fiuzat, Maurice L. Albertson, «Experimental Study of Cross -Flow Turbine,» Journal of Hydraulic Engineering, vol. 114, 1988.

[7] G. Henrik Lund, «The role of compressed air energy storage (CAES) in future sustainable energy systems,» Energy Conversion and Management, vol. 50, pp. 1172-1179, 2009.

[8] Mustafa E. Amiryar, Keith R. Pullen, «A Review of Flywheel Energy Storage System Technologies and Their Applications, » Applied sciences, vol. 7, 2017.

[9] A. Nadia, Optimisation Du Stockage Des Energies Renouvelables, paf, Éd., 2014.

[10] S. H. Antonio Luque, Handbook of Photovoltaic Science and Engineering, WILEY, 2003.

[11] F. COUPAN, Stockage pour les énergies renouvelables : évaluation et modélisation de la batterie plomb-acide, HAL, 2017.

[12] and F. L. Leonardo Giorgi, "Fuel Cell Applications Fuel Cell Applications Fuel Cell Applications," *Open Fuel Cells J.*, vol. 6, pp. 1875–9327, 2013.

[13] D. des R. Accidentels, “Pile à combustible stationnaire : contexte réglementaire et normatif international et national (risques potentiels) RISQUES POTENTIELS,” 2017.

[14] K. B. Rafael-Antonio Linares-Lamus, Melika Hinaje, “Alimentation d’une bobine supraconductrice par une pile à hydrogène,” in *Jeunes Chercheurs en G´enie Electrique (JCGE’14)*, 2014, no. June, pp. 1–10.

[15] L. ANTONI, “La pile à combustible : Un convertisseur d’énergie d’avenir,” Grenoble, 2007.

[16] S. S. R. Ajay Ahuja, D.R. Waghole, “Fuel Cell Technologies for Automotive Applications,” *J. power Electron. power Syst.*, vol. 12, no. 1, pp. 1–15, 2022.

[17] K. Jain and K. Jain, “Hydrogen Fuel Cell : A Review of different types of fuel Cells with Emphasis on Hydrogen Fuel Cell : A Review of different types of fuel Cells with Emphasis on PEM fuel cells and Catalysts used in the PEM fuel cell,” *Int. J. All Res. Educ. Sci. Methods*, vol. 9, no. 9, 2021.

[18] P. Breeze, “Chapter 8 - Hydrogen Energy Storage,” in *Power System Energy Storage Technologies*, P. Breeze, Ed. Academic Press, 2018, pp. 69–77.

[19] F. Barbir, “Chapter Ten - Fuel Cell Applications,” in *PEM Fuel Cells (Second Edition)*, Second Edition., F. Barbir, Ed. Boston: Academic Press, 2013, pp. 373–434.

[20] Guoping Wang, Hongqing Wang, Benhe Zhong, Lei Zhang, Jiujun Zhang, «Supercapacitors’ Applications,» chez Electrochemical Energy, 2015, pp. 479-492.

[21] John Schönberger, «Modeling a Supercapacitor using PLECS,» Application Example, 8005 Zürich.

[22] Lei Zhang, Xiaosong Hu, Zhenpo Wang, Fengchun Sun, David G. Dorrell, «A review of supercapacitor modeling, estimation, and applications: A control/management perspective, » Renewable and Sustainable Energy Reviews, vol. 81, pp. 1868-1878, 2018.