People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
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COURSE MATERIAL

Energy Transport and Storage

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First Year Master's (M1) Students in Mechanical and Energy Engineering

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Foreword

This course material, entitled "Energy transport and storage", is intended for first-year students of the Master’s degree in Mechanical Engineering, speciality Energy. The content of this teaching material is aligned with the Master’s programme in Mechanical Engineering taught in the departments of mechanical engineering.

Basic knowledge in energy transport and storage is presented in this course to better understand and assimilate the content of this teaching material. Energy transport and storage is a branch of energy engineering that deals with different forms of energy, their transportation and conservation. In this area, efficient energy management is paramount, while storage and transport technologies are the key operational aspects.

The objective of this teaching material is to introduce students to the different technologies and methods used in energy transport and storage, with emphasis on technical and economic aspects. Fundamentals are used in this course to establish a comprehensive understanding of energy systems and their optimization.

This educational document is divided into four chapters:

- The first chapter is devoted to the different forms of energy
- The second is energy management: production, processing, transport and storage
- The third chapter focuses on energy transport
- The fourth covers energy storage in its various forms

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1 Introduction

Energy plays a fundamental role in the functioning of natural systems and human societies. It is at the core of all physical, chemical, and biological processes and constitutes a key factor in economic development, technological progress, and social organization. All human activities—industrial production, transportation, heating, electricity generation, and even biological life—depend directly or indirectly on the availability and use of energy.

From a physical standpoint, energy is neither created nor destroyed, in accordance with the principle of conservation of energy. However, it can be converted from one form to another. In practice, all technological systems operate by transforming energy from an available form into a useful form. For instance, the chemical energy stored in fuels or food is converted into mechanical work, electricity, or thermal energy. Ultimately, most energy transformations result in the production of heat, which is dissipated into the environment.

Understanding the nature of energy, its various forms, and the laws governing its transformation is therefore essential for the study of energy transport and storage systems. This chapter introduces the fundamental concepts related to energy, its definition, its forms, and the units used to quantify it.

2 Definition

The term energy originates from the Greek word energeia, meaning “activity” or “force in action.” In physics, energy is an abstract and multifaceted concept, which makes its definition non-trivial. In a general sense, energy can be defined as the capacity of a system to produce an effect or to cause a change. More precisely, energy is the physical quantity that characterizes the ability of a system to modify the state of another system through the transfer of work or heat. It is a property of systems, particles, or radiation, and it manifests itself through transformations and exchanges. According to the principle of conservation of energy, the total energy of an isolated system remains constant over time. Energy may change form, but it is not lost. Furthermore, the theory of relativity establishes an equivalence between mass and energy through Einstein's relation:

$$E = mc^2$$

where mmm is the mass and ccc is the speed of light in vacuum. This relation highlights the extremely high energy content associated with mass, which becomes significant in nuclear processes.

In real systems, although energy is conserved, its quality tends to degrade. Most energy consumed in practical applications ultimately dissipates as thermal energy. Moreover, the fraction of energy that can be converted into useful work is limited by thermodynamic laws. As a result, the efficiency of energy conversion systems—such as thermal engines, gas turbines, or internal combustion engines—is always less than 100%.

2.1 Energy as Motion or the Capacity to Produce Motion

From a physical perspective, energy can be broadly classified into two main categories:

- Potential energy, which is associated with stored energy due to position, configuration, or internal stresses within a system (for example, gravitational, elastic, or chemical energy).
- Kinetic energy, which is associated with motion. This category includes mechanical energy, thermal agitation of particles, electromagnetic radiation (light), acoustic energy, and electrical energy resulting from the motion of electric charges.

These forms of energy can be converted into one another depending on the physical processes involved.

2.2 Energy as the Capacity to Transform Matter

Beyond motion, energy also enables the transformation and structuring of matter. It allows the synthesis of new materials and substances that do not exist naturally, as well as the modification of physical and chemical properties of existing materials. This aspect of energy is particularly important in industrial processes, materials science, and chemical engineering.

Despite its multiple manifestations, energy remains a unified physical concept. The diversity of its forms reflects the variety of mechanisms through which it can be stored, transferred, and transformed.

2.3 Units of Energy

In the International System of Units (SI), energy is measured in joules (J), in honor of James Prescott Joule (1818–1889), who demonstrated the equivalence between mechanical work and heat.

The joule has replaced older units such as the calorie (used for thermal energy) and the kilogram-meter (used for mechanical work). The following equivalences apply:

- 1 calorie = 4.187 joules,
- 1 kg-m = 9.806 J

At the human and industrial scale, the joule is often too small to be practical. Therefore, multiples of the joule are commonly used:

- ✓ kilojoule (kJ) = 1,000 joules
- ✓ megajoule (MJ) = 1 million joules
- ✓ Other prefixes : Tera = 1,012, Peta = 1,015 and Exa = 1018.
- ✓ gigajoule (GJ) = 1 billion joules

In engineering and energy studies, several non-SI units are also widely used.

1 kWh =3.6×106 J =3.6 MJ

It corresponds to the energy delivered by a device with a power of 1 kW operating for one hour.

The tonne of oil equivalent (toe) is used to compare different energy sources based on their energy content. It represents the amount of energy released by the combustion of one tonne of crude oil:

1 TOE = 41.86 billion joules = 41.86 GJ

This unit is widely employed in national and international energy statistics.

The electronvolt is a unit of energy used in atomic and nuclear physics. It corresponds to the kinetic energy gained by an electron accelerated through a potential difference of one volt:

The unit of energy, whether potential, mechanical, electrical, chemical or thermal, is the Joule (symbol J), a unit adopted in homage to James Preston Joule (English physicist 1818-1889), who demonstrated and measured the equivalence of mechanical and thermal energy.

1 electron volt = = 1,6.10−19 joules.

Tonne of oil equivalent (toe)

The tonne of oil equivalent (toe) is a unit of measurement used to compare the equivalent of energy in oil. It represents the quantity of energy contained in one tonne of crude oil.

1 TOE = 41.86 billion joules = 41.86 GJ

This is the average amount of energy released when one tonne of oil is burned.

Energy and power are two different notions.

Electron volt (eV)

The electron volt (eV) is an energy unit used in atomic and nuclear physics. This is the kinetic energy acquired by an electron accelerated from rest by a potential difference of one volt.

1 electron volt = = $1,6.10^{-19}$ joules.

British Thermal Unit (BTU)

The British Thermal Unit (Btu or BTU) is an Anglo-Saxon energy measurement unit, which represents the amount of heat needed to raise the temperature of an English pound of water by 1° F (Fahrenheit) at the constant pressure of an atmosphere.

1 BTU = 1,055.06 Joules.

There is also the British Thermal Unit per hour (also called the British Thermal Unit per hour, in both cases symbolized by BTU/h) which represents the power of a system delivering or consuming one BTU in an hour (for 1 BTU/h).

One watt = 3.412 14 BTU/h.

1 BTU = 1 055,06 joules.

3 Energy and power

Energy and power are closely related physical quantities, but they represent different concepts. **Energy** characterizes the capacity of a system to perform work or produce an effect, whereas

power represents the rate at which energy is produced, transferred, or consumed. In other words, power corresponds to an energy flow over time.

The relationship between energy and power is analogous to the relationship between distance and speed. Just as speed is the rate of change of distance with respect to time, power is the rate of change of energy with respect to time.

Mathematically, power is defined as:

and

$$P = \frac{dE}{dt}$$

where:

- P is the power (in watts),
- E is the energy (in joules),
- t is the time (in seconds).

For a system operating at constant power, the energy exchanged over a time interval $[t_1, t_2]$ is given by:

$$E = \int_{t_1}^{t_2} P dt = P(t_2 - t_1)$$

The SI unit of power is the watt (W), defined as:

1 watt (W)= 1 joule per second (1 J / s).

This means that a device with a power of 1 watt transfers or consumes one joule of energy per second.

Example: Calculation of Energy from Power

A microwave oven operates at a constant power of 450 W for a duration of 5 hours. Calculate the energy consumed.

Energy in watt-hours

$$E = P * t = 450 * 5 = 2250\ Wh$$

Conversion to kilowatt-hours

$$E = \frac{2250}{1000} = 2.25\ kWh$$

Conversion to joules

Since:

$$1kWh = 3.6 * 10^6 J$$

$$E = 2.25 * 3.6 * 10^6 = 8.1 * 10^6 J = 8.1MJ$$

The microwave consumes 2.25 kWh, which corresponds to 8.1 MJ of energy.

This example highlights the importance of distinguishing between power, which characterizes the instantaneous operation of a device, and energy, which quantifies the total consumption over a given period. In energy transport and storage systems, this distinction is essential for sizing equipment, evaluating efficiency, and estimating operating costs.

4 The different forms of energy

Energy classification is complex given the diverse processes of energy transformation and conversion. Energy appears in various forms that naturally occur in our environment.

4.1 Thermal energy:

Temperature modification: It is the manifestation of heat, which is actually the energy of random movements of atoms and molecules in a solid, liquid or gaseous body. The more this kinetic energy increases, the more there is temperature and therefore heat. Heat is manifested on an object by different changes of state that can be converted into directly usable energy, such as electrical energy.

Example: thermal energy produced by the combustion of raw materials (coal, gas, wood, biomass) is used in a flame fired power plant to heat water (or another liquid) and produce water vapour, which will itself drive the movement (mechanical energy) of a turbine and alternator to produce electrical energy.

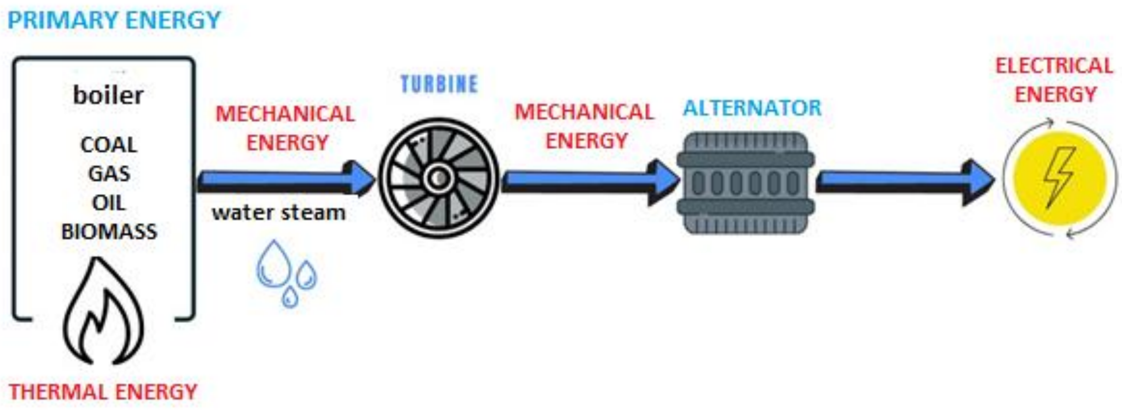


Figure 1. 1 Production of electricity through thermal energy by burning coal, gas or oil or biomass. (https://www.choisir.com/energie/articles/117578/ce-quil-faut-savoir-sur-les-centrales-electriques (accessed 13/06/2023)

4.2 Mechanical energy:

Mechanical energy is the form of energy associated with the motion and position of macroscopic objects. It generally appears in two complementary forms: **kinetic energy** and **potential energy**.

- ✓ **Kinetic energy** is the energy associated with the motion of an object. It depends on the mass of the object and the magnitude of its velocity. The greater the velocity of an object, the higher its kinetic energy.
- ✓ **Potential energy** is the energy stored in an object due to its position in a force field, most commonly the gravitational field. An object at rest can possess potential energy if it is located at a certain height relative to a reference level. This stored energy can be converted into kinetic energy when the object is allowed to move under the effect of the force field.

In mechanical systems, energy is continuously exchanged between kinetic and potential forms, while the total mechanical energy remains conserved in the absence of dissipative effects such as friction.

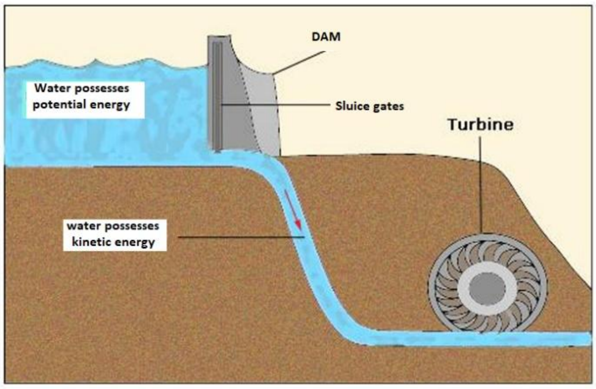


Figure 1. 2 Potential energy from water is transformed into kinetic energy that drives the turbine and produces electricity (https://www.maxicours.com/se/cours/conversion-de-l-energie-mecanique-dans-une-chute-d-eau/ (accessed on 13/06/2023)

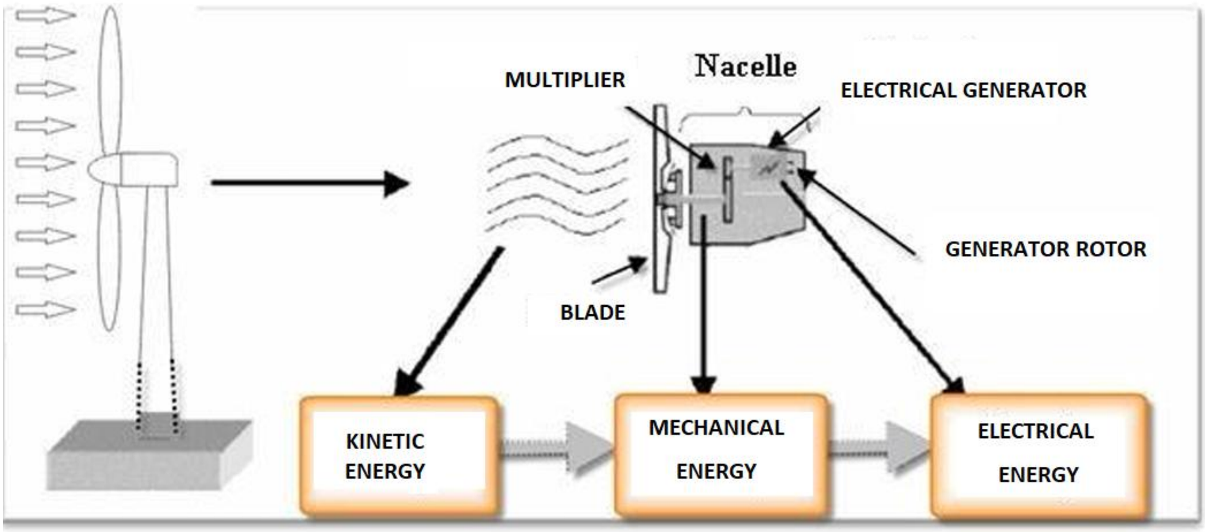


Figure 1. 3 Conversion of wind kinetic energy into electricity

4.3 Nuclear energy:

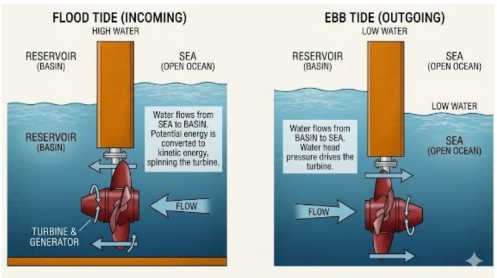
Nuclear energy is the energy of the bonding of the constituents of the nucleus of atoms. It is a fossil energy because it comes from a raw material that is an element originally created in the stars and stored in planets, including the earth. Nevertheless, nuclear energy is considered to be fission (e.g. fission of uranium 235 or plutonium 239) or fusion (fusion of deuterium and tritium into helium) as an alternative to other fossil fuels since it does not emit CO2 and offers a certain energy independence. Its great disadvantage that it raises problems of safety and storage of radioactive waste which we do not (yet) know how to treat to make them harmless.

4.4 Hydraulic power:

Water energy is the energy provided by the movement of water in all its forms: waterfalls, rivers, sea currents, waves. Water energy is actually kinetic energy related to the movement of water such as in marine currents, rivers, tides, waves or the use of potential energy of gravity as in the case of waterfalls and dams.

Waterfalls

Marine Currents



Marine Currents

Ocean Waves

Figure 1. 4 Types of Marine and Hydraulic Energy Sources

4.4.1 Wind energy:

Wind energy is the use of wind kinetic energy (originally from solar radiation) as a driving force. This energy can be used in two ways:

Conversion into mechanical energy: wind is used to move a vehicle (sailboat or sailing cart), to pump water (wind turbines for irrigation or drinking of livestock) or to turn the wheel of a mill;

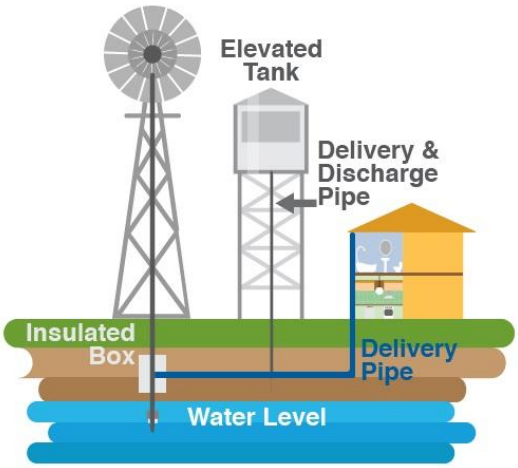


Figure 1. 5 Wind energy for water pumping

The production of electrical energy: the wind turbine is coupled to an electric generator to create direct or alternating current. The generator is connected to a power grid or operates within an "autonomous" system with a backup generator (for example, a generator set), battery farm or other energy storage device. An electricity-generating wind turbine is sometimes referred to as a wind generator.

Figure 1. 6 Wind power for electricity generation

4.4.2 Radiant energy:

It is contained in the electromagnetic waves of the sun's radiation. The visible part of these waves is manifested by light, like that emitted by the Sun to illuminate us. In his daily life, the man has managed to recreate radiant energy through the microwave oven running to warm a dish, or the light of an electric bulb. Solar energy is a form of radiant energy, which can produce thermal energy (solar thermal) or be transformed into electricity (photovoltaic panels).

Note: Photovoltaic panels convert part of the light from solar radiation into electricity, the rest heating the panels that must cool in contact with ambient air. Solar thermal collectors convert solar radiation into heat by absorbing it through a black surface, itself in contact with a fluid (often water) that transports this heat to the user (heating or water heater). This system does not produce electricity but provides hot water and supplies the boilers.

Figure 1. 7 Photovoltaic panels (electricity generation)

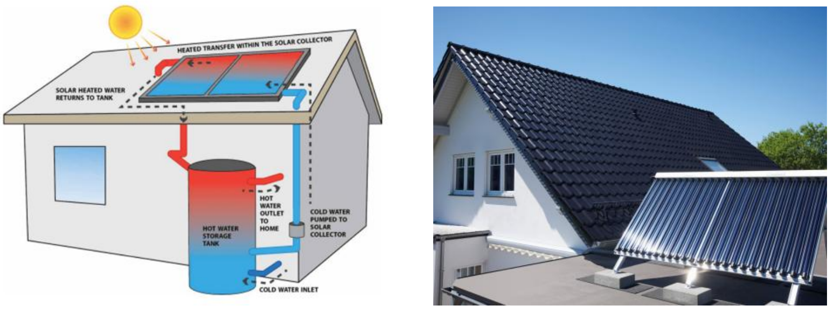


Figure 1. 8 Solar collectors to produce hot water

Solar radiation is also converted into chemical energy in plants by photosynthesis.

4.4.3 Chemical energy:

It occurs when the bonds of atoms in molecules contained in an object are modified or broken. This chemical transformation or reaction releases energy, used as such or transformed in turn into another form of energy.

Example: burning raw materials such as wood or coal is a release of chemical energy, producing heat (thermal energy) or electricity by burning hydrogen in fuel cells.

Industrial scale in a cogeneration engine: The movement of the fuel engine is used mechanically, usually to generate electricity, and the waste heat produced is injected into the heating networks of a community.).

4.4.4 Electrical energy :

It is caused by the movement of electrons in a conductor. This is the movement of electrical charges (also known as energy transfers) between two systems. The conversion of electrical energy is thus manifested concretely between two types of systems: generators (or suppliers) and receivers (or receivers). Electricity is a secondary energy or an energy vector because it is generated from the transformation of primary energy through a conversion system.

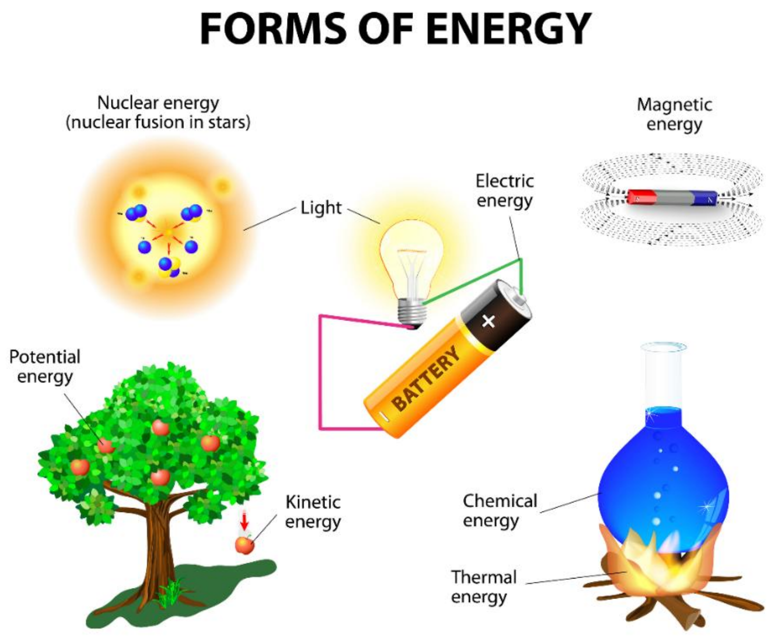


Figure 1. 9 Different forms of energy

In conclusion, it can be said that these different forms of energy are essentially thermal and mechanical.

Example: mechanical energy produced by a wind mill is primary energy. If this mechanical energy is converted into electricity, the electrical energy produced is considered as secondary energy since it is obtained by transformation.

5 Sources of energy

An energy source is any phenomenon from which usable energy can be extracted.

These sources of energy can be natural or artificial.

- ✓ Primary energy: available in nature before transformation.
- ✓ Secondary energy: it comes from the transformation of a form of primary energy to be exploited, if necessary after transport.
- ✓ Final energy: it arrives at the consumer. It is the one charged to him
- ✓ Useful energy: it is the share of final energy actually used to satisfy the user's need.

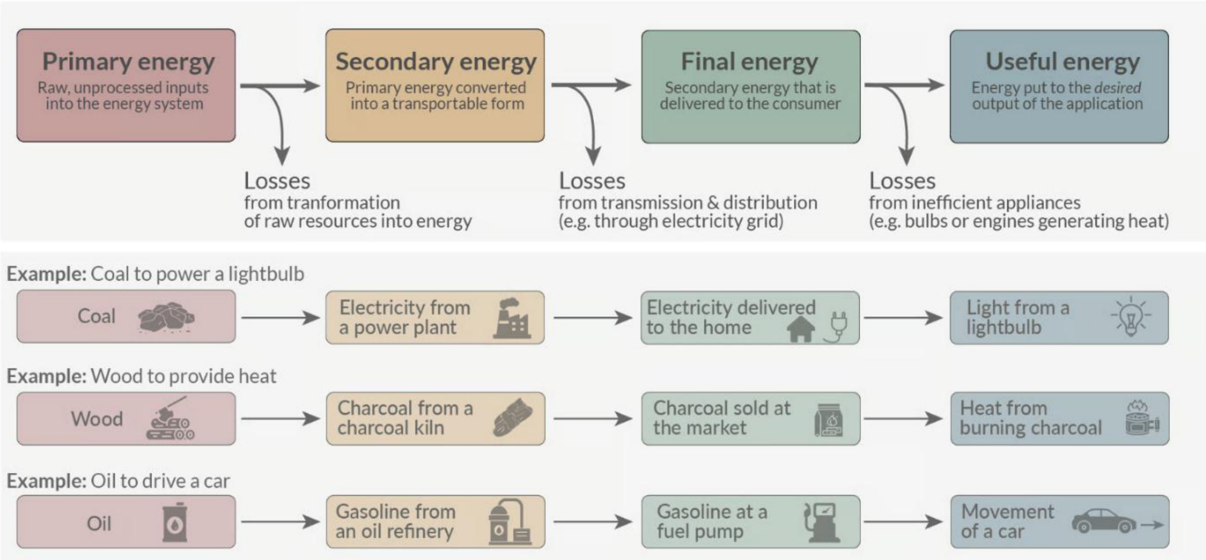


Figure 1. 10 From Primary to Useful Energy: The Energy Conversion Chain

To move from primary energy to useful energy, different steps are necessary (extraction and processing, transport and distribution). Each of them generates losses, mainly in the form of heat.

- ✓ Secondary energy = primary energy x conversion efficiency;
- ✓ Final energy = secondary energy x transport efficiency;
- ✓ Useful energy = final energy x efficiency.

The ratio of total primary energy required to produce a form of final energy to the amount of final energy produced is the primary energy factor.

Table 1. 1 Energy Classification and Characteristics

Forms of Energy	**Characteristics**
Primary Energy	Raw energy sources extracted directly from nature (e.g., crude oil, coal, wind, solar radiation) before any conversion.
Secondary Energy	Transformed or converted energy that can be stored, transported, or routed (e.g., electricity from a power plant, refined gasoline).
Final Energy	Energy that has been transported to its point of consumption and is delivered to the end-user (the energy that is billed/invoiced).
Useful Energy	The actual energy that performs the desired work or service, allowing an appliance or system to function (e.g., light from a bulb, mechanical rotation from a motor) after accounting for efficiency losses.

Energy sources can be renewable or non-renewable. Non-renewable energy sources are naturally limited in quantity. These are raw materials that cannot be reproduced quickly. The limited amount of material needed for energy production means that new modes of production must be found in the long run.

Fossil and fissile fuels. Fossil-based energies are those that come from the decomposition of organic matter, mainly plant, over millions of years. These are coal, peat, lignite, coal, oil and natural gas. Fissile energy is the energy produced by the fission of an atomic nucleus (usually uranium).

A renewable energy is an energy that benefits from natural and rapid renewal. They depend on elements that nature constantly renews. From a human point of view, they are considered inexhaustible: the sun, water, wind, wood, biomass, geothermal. However, these sources are not unlimited. In particular, biomass is only renewable if only the locally renewed share is used each year.

6 Conclusion

This chapter presents the different concepts and forms of energy, giving a detailed overview of key energy concepts. By exploring mechanical, kinetic, fossil and renewable energies, we have brought to light the richness and diversity of energy resources, their distinctive characteristics and implications in our modern understanding of energy systems.

1 Introduction

One of the major global challenges today is achieving a balance between energy production and energy consumption. Several factors contribute to this issue, including:

- Growth of the world population
- Increasing energy demand
- Reduction in energy production capacity
- Depletion of natural resources
- Rising energy costs
- Environmental and ecosystem degradation
- Rapid expansion of wind and photovoltaic power generation systems

These challenges raise two fundamental questions for the future:

- How can energy be consumed in an effective and efficient manner?
- How can sustainable development be achieved while taking environmental aspects into account?

Energy management has therefore become an essential strategy for improving energy efficiency, reducing environmental impacts, and ensuring sustainable energy use.

This chapter begins by introducing the concept of energy management and its main objectives, particularly the efficient use of energy resources and environmental protection. It then presents the energy management process, emphasizing a comprehensive approach that includes the development of an energy policy and strategic energy planning.

The chapter also discusses the requirements for implementation and operation, including competence management, internal and external communication, and operational control. Finally, it examines the verification phase through monitoring, measurement, and internal audits, before highlighting the importance of continuous improvement in achieving long-term energy performance and sustainability.

2 Energy management

Energy management refers to the set of practices, policies, and technologies implemented to monitor, control, and optimize energy use in various sectors such as industry, commerce, infrastructure, and residential buildings.

The main objectives of energy management are to:

- ✓ Ensure the efficient and sustainable use of energy resources;
- ✓ Conserve natural resources;
- ✓ Reduce energy costs;
- ✓ Protect the climate and the environment;
- ✓ Reduce greenhouse gas emissions.

All these objectives must be achieved while ensuring continuous access to the energy required by users.

Energy management is closely related to environmental management, production management, logistics, and other established business functions. The VDI 4602 directive defines energy management as follows: *"Energy management is the proactive, organized, and systematic coordination of energy supply, conversion, distribution, and use to meet requirements while taking environmental and economic objectives into account."*

Therefore, energy management can be considered a systematic approach aimed at optimizing energy efficiency in accordance with specific political, economic, and environmental objectives through the application of engineering and management techniques.

3 Energy management processes

Effective energy management requires a holistic approach that considers energy consumption in all aspects of a system, from design and construction to operation and maintenance.
An energy management system is based on a continuous and systematic process aimed at improving energy performance. Its main purpose is to enhance energy efficiency within organizations and to prevent the recurrence of inefficient energy consumption practices. The principle of such a system is based on the following steps:

- ✓ Identification of opportunities for improvement;
- ✓ Implementation of targeted and planned actions;
- ✓ Measurement and evaluation of performance;

- ✓ Adjustment and corrective actions when necessary;
- ✓ Definition of new objectives for continuous improvement.

The following flowchart illustrates the main steps involved in the energy management process.

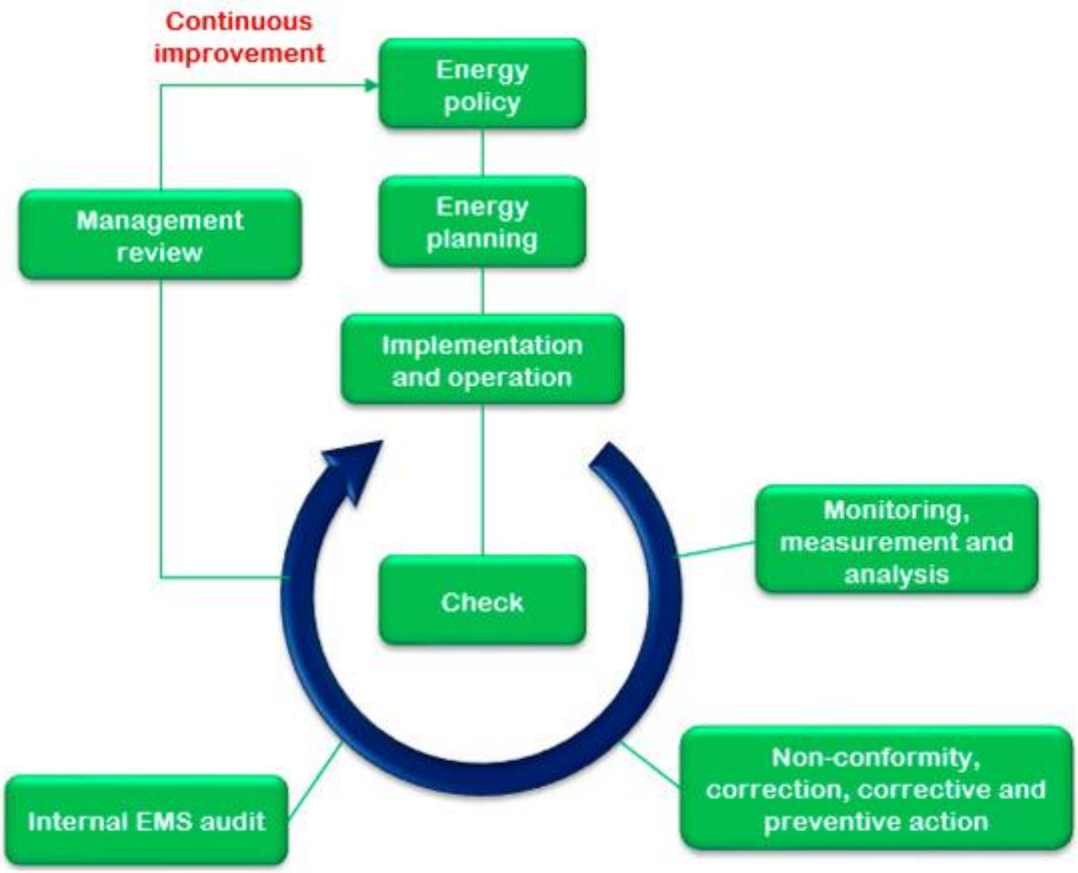


Figure 2. 1 Steps in an energy management process

3.1 Energy policy

An energy policy is a formal document that represents a written commitment by a company or government to manage its energy resources effectively and responsibly. This policy sets out the guiding principles, objectives and strategies that the company implements to optimize its energy use.

- Reduction of energy consumption, including:
  - ✓ the reduction of needs (sobriety)
  - ✓ improving the energy efficiency of installations,
- the adoption of renewable energy sources,

- compliance with environmental regulations, and other initiatives to minimize the company's carbon footprint

Energy policy is an essential step in the process of energy management. It provides a reference framework for decision-making and the development of concrete action plans to achieve energy targets. It can also be used to communicate the company's commitments to environmental sustainability to its internal and external stakeholders.

3.2 Energy planning:

Planning is one of the most important parts of the energy management program. It includes these steps, some of which require analysis:

- Identify energy related maintenance functions.
- Estimate the energy related maintenance costs of the current facility.
- Determine the current maintenance status of each major energy system and each major energy-consuming equipment component within the facility. Decide which energy-related maintenance tasks should be performed immediately and which can be delayed.
- Develop a list of current planned maintenance tasks and planned maintenance to be performed.
- Determine initial monitoring procedures.
- Select a set of objectives for the maintenance function

3.3 Common Energy Management Techniques

Several techniques are commonly used in energy management to improve energy efficiency, reduce operating costs, and optimize system performance in industrial, commercial, and residential sectors.

3.3.1 Energy Audits

Energy audits are systematic evaluations of energy consumption within a facility. Their objective is to identify energy losses, inefficient equipment, and opportunities for energy savings. Audits may be preliminary, detailed, or investment-grade depending on the level of analysis required.

3.3.2 Load Management

Load management aims to control and optimize energy demand during peak consumption periods. This technique helps reduce electricity costs and improve grid stability by shifting or reducing non-essential loads.

3.3.3 Smart Monitoring Systems

Modern energy management relies on intelligent monitoring systems using sensors, smart meters, and automation technologies. These systems provide real-time data on energy consumption, allowing rapid detection of abnormal energy use and performance optimization.

Figure 2. 2 Smart Home Energy Monitoring.

3.3.4 Process Optimization

Process optimization consists of improving the efficiency of industrial operations and equipment. This includes optimizing operating parameters, recovering waste heat, improving insulation, and using high-efficiency technologies.

3.3.5 Preventive Maintenance

Preventive maintenance helps maintain equipment performance and reduce unnecessary energy losses. Regular inspection and maintenance improve system reliability and energy efficiency.

3.3.6 Integration of Renewable Energy

The integration of renewable energy sources such as solar and wind power contributes to reducing dependence on fossil fuels and improving environmental sustainability.

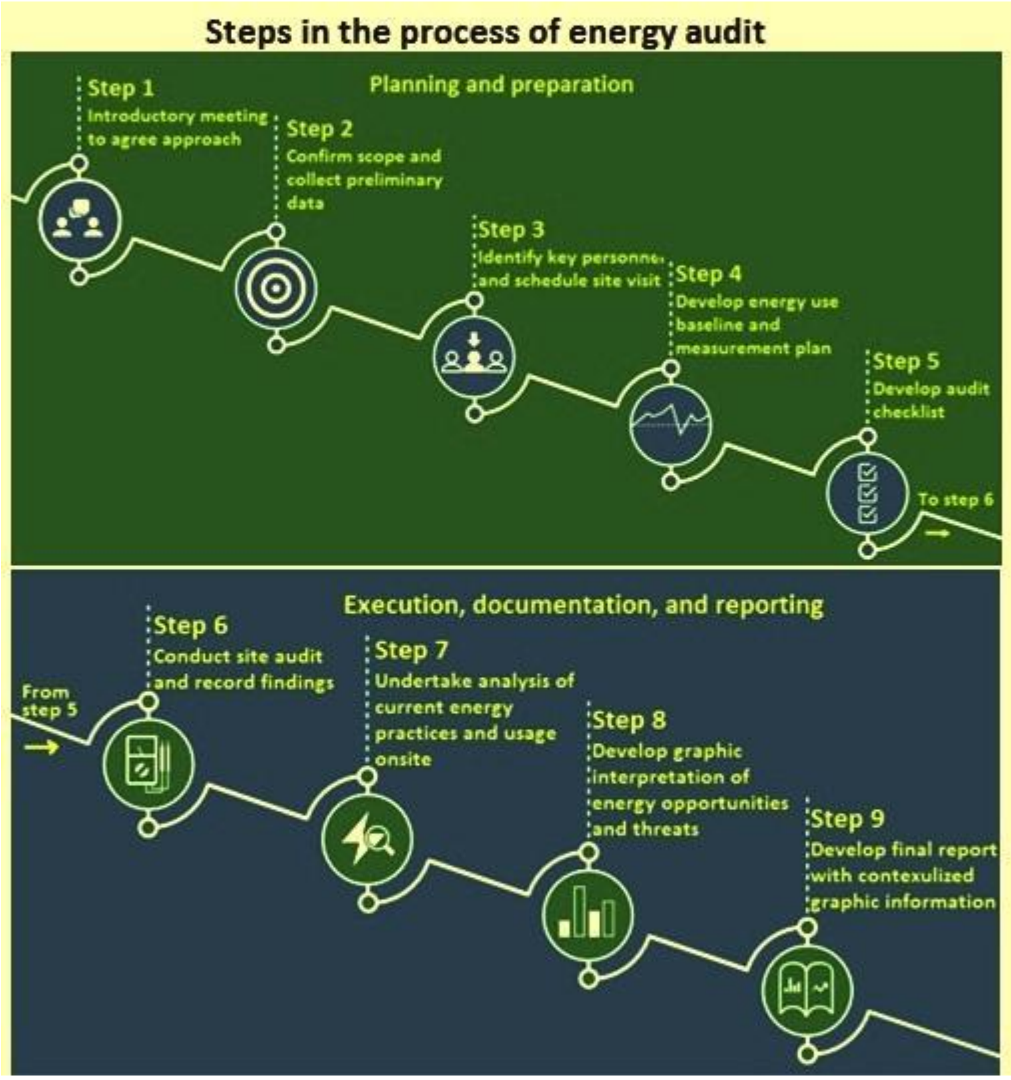


Figure 2. 3 Steps in the process of energy audit. Source (https://www.ispatguru.com/energy-audit-in-steel-plant/?utm_source=chatgpt.com#google_vignette) accessed on 08/12/2025

3.3 Implementation and operation

The implementation and operation phase ensures the effective application of the Energy Management System (EnMS) within the organization. It includes resource management, personnel training, communication, documentation, operational control, and energy-efficient practices to improve overall energy performance.

3.3.1 Competency Management and Training Needs

Successful implementation of an energy management program depends on the competence of personnel involved in energy-related activities. Organizations must identify the required skills and provide appropriate training programs to improve employees' technical and managerial capabilities.

- ✓ **Internal competency management:** concerns the training of employees, operators, maintenance teams, and managers on energy-efficient practices and operational procedures.
- ✓ **External competency management:** involves collaboration with external experts, consultants, suppliers, and training institutions to enhance technical knowledge and adopt advanced energy management practices.

Training programs should focus on:

- Energy efficiency techniques,
- Monitoring and measurement methods,
- Maintenance procedures,
- Safety and environmental practices,
- Operation of energy systems and equipment.

3.3.2 Awareness

- Energy awareness plays a key role in improving organizational energy performance. All personnel should understand the importance of energy efficiency and their contribution to reducing energy consumption.
- **Internal awareness:** includes awareness campaigns, workshops, meetings, and posters intended to encourage employees to adopt energy-saving behaviors.
- **External awareness:** concerns communication with customers, suppliers, stakeholders, and the community regarding the organization's energy policy and environmental commitment.

Awareness activities help create an energy-conscious culture within the organization.

3.3.3 Energy Performance Communication

Effective communication ensures the proper exchange of information related to energy performance indicators, objectives, and improvement actions.

- **Internal communication:** includes reporting energy consumption data, operational instructions, performance indicators, and feedback among departments.
- **External communication:** involves sharing relevant energy information with authorities, clients, suppliers, and certification bodies when necessary.

Clear communication improves coordination and supports decision-making processes.

3.3.4 Documentation Management

Documentation management is essential for ensuring consistency, traceability, and compliance within the Energy Management System. Organizations must establish and maintain documented information related to:

- ✓ Energy policies,
- ✓ Operational procedures,
- ✓ Monitoring records,
- ✓ Maintenance reports,
- ✓ Energy audits,
- ✓ Performance evaluations.

Proper documentation facilitates system monitoring, verification, and continuous improvement.

3.3.5 Operational Control and Proficiency

Operational control aims to ensure that energy-consuming processes operate under optimal conditions to reduce energy losses and improve efficiency.

3.3.1.1 Maintenance Tracking

Regular maintenance of equipment and energy systems is necessary to maintain high performance and avoid unnecessary energy consumption. Maintenance activities include:

- ✓ Preventive maintenance,
- ✓ Corrective maintenance,
- ✓ Inspection and calibration of instruments,
- ✓ Monitoring equipment performance.

3.3.1.2 Definition and Monitoring of Energy Performance Criteria

Organizations should define energy performance indicators (EnPIs) and continuously monitor them to evaluate system efficiency and identify improvement opportunities. Common indicators include:

- ✓ Specific energy consumption,
- ✓ Energy efficiency ratio,
- ✓ Energy intensity,
- ✓ Equipment performance efficiency.

3.3.6 Design Project Management

Energy performance should be integrated into the design and development of new facilities, systems, and processes. During project design, organizations must consider:

- ✓ Energy-efficient technologies,
- ✓ Thermal insulation,
- ✓ Renewable energy integration,
- ✓ Equipment efficiency,
- ✓ Lifecycle energy costs.

Proper design management significantly reduces long-term operational energy consumption.

3.3.7 Energy Considerations in Purchasing

Purchasing activities directly influence the energy performance of an organization. Therefore, energy efficiency criteria should be integrated into procurement decisions.

3.3.1.3 Energy Procurement

Organizations should evaluate energy sources based on:

- ✓ Cost,
- ✓ Availability,
- ✓ Environmental impact,
- ✓ Reliability,
- ✓ Renewable energy potential.

3.3.1.4 Product and Service Procurement

Energy-efficient products and services should be prioritized during purchasing processes. This includes:

- ✓ High-efficiency equipment,
- ✓ Low-energy appliances,
- ✓ Energy-efficient lighting systems,
- ✓ Maintenance and technical services supporting energy optimization.

Considering energy performance during procurement contributes to reducing operating costs and improving sustainability.

3.4 Verification

This section also explains the requirements for internal audit and provides a detailed explanation of the management review.

3.5 Monitoring and measurement and analysis:

This monitoring focuses on what needs to be monitored, measured, analyzed and evaluated, and when these procedures need to be performed. Any significant difference between actual and projected energy performance shall be investigated and corrected. Compliance with legal and other requirements must also be assessed.

3.6 Internal audit

This audit is designed to provide information on whether the energy management system is delivering the required results. The program should incorporate audit reporting frequency, methods, responsibilities, planning and requirements. The audit criteria and scope must be agreed upon and audits must be conducted “objectively” and results communicated to the relevant management.

3.7 Management review

The review shall be conducted at scheduled intervals, including the status of actions already agreed upon and any changes to internal and external issues relevant to the Energy Management System. The review should also consider risks and opportunities, information on the performance of the energy management system, improvement in energy performance and the extent to which energy targets and objectives have been met. The outcome of the review should be an assessment of the effectiveness of the Energy Management System, actions to achieve the objectives and implications for changes to the Energy Management System and business strategies.

3.8 Improvement

Following the performance evaluation, this section covers issues that need to be resolved such as non-conformances, corrective actions and continuous improvement to improve performance in the future.

3.9 Non-compliance and corrective actions

Corrective actions to address non-conformities must be taken and the effectiveness of these actions reviewed. Assess proactive actions to eliminate the cause(s) of non-compliance so that it does not occur or recur elsewhere.

3.10 Continuous improvement

The relevance, adequacy and effectiveness of the Energy Management System must be continuously improved. The organization must demonstrate continuous improvement in its energy performance.

4 Conclusion

This chapter presented energy management as a complex and strategic process to optimize the use of energy resources. By outlining its objectives, principles and stages, we have highlighted the crucial importance of a systematic and holistic approach to coordinating energy production, processing, transport and storage, both economically and environmentally.

1 Introduction

Energy transportation is a critical component of modern energy systems, moving electricity, natural gas, oil and other forms of energy from production sites to consumption centres. Different forms of energy require specific transport infrastructures. Here is an overview of the main modes of energy transport:

2 Transport of Fuels

A fuel is a substance that, when reacting with an oxidizing agent, releases energy in the form of heat or light. Fuels are often used to produce thermal, mechanical or electrical energy.

Fuel transportation is a critical component of the energy supply chain, allowing for the movement of energy sources such as oil, natural gas, coal, and other fuels from the place of production to the point of consumption. Several modes of transport are used depending on the type of fuel, distance to travel and available infrastructure.

3 Natural gas transportation:

Natural gas is frequently extracted from underground reservoirs using drilling processes, and can also be generated in conjunction with crude oil extraction. Composed primarily of methane, which generally constitutes more than 90% of its composition, natural gas may have variations in its other constituents, such as ethane, propane and butane, depending on the source. This versatile energy resource is used in a variety of applications, such as power generation, residential and commercial heating, cooking, and as fuel for vehicles. The industry also uses natural gas as a key raw material in chemical manufacturing.

Gas can be transported through pipelines, which are large underground pipelines, or by ships specializing in the transport of liquefied natural gas.

3.1.1 Transportation by pipelines:

Natural gas pipelines transport natural gas over long distances from production sites to consumption centres. Before being transported, natural gas must be compressed at a high pressure, for which steel pipes capable of withstanding pressures up to 90 bar are used. The gas pipelines are mostly land based, either buried at about a metre deep in inhabited areas or laid directly on the ground in desert zones or hard-soil zones.

Gas pipeline crossing the desert | Locally above-ground gas pipelines

Figure 3. 1 Land-based gas pipelines

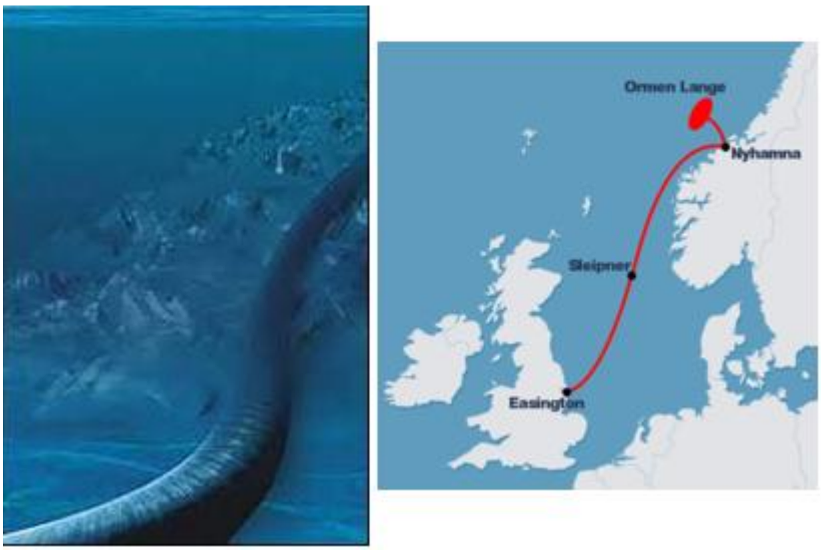


Figure 3. 2 Land Gas Pipelines The Langeled is the world’s longest subsea pipeline, located in the North Sea, connecting Norway to the UK. It is 1,166 kilometres long..

These pipes consist of steel tubes with a thickness of a few millimetres and a diameter ranging between 0.9 and 1.40 metres, connected by welding. Within these pipelines, natural gas flows at a speed of 30 km/h, propelled by the pressure difference between the deposit (or the processing phase) and the points of consumption. To maintain this high pressure of about 70 bar, compression stations are installed every 80 to 120 km.

Natural gas transport through pipelines involves a carefully orchestrated process. The main stages of natural gas transportation through pipelines are as follows:

Compression: Before entering the pipelines, natural gas is compressed at high pressure. Compression stations are used to increase the pressure of gas, making it easier to move through pipelines over long distances.

Pipeline injection: Once compressed, natural gas is injected into the pipeline system from production facilities or specific injection points.

High pressure transport: Natural gas moves through pipelines due to the pressure difference between the starting point (usually the production site or compressor station) and the arrival point (Consumer site or other point of delivery). Pipelines are designed to withstand high pressures, typically in the tens of bars range.

Monitoring and regulation: Monitoring systems are installed along pipelines to monitor flow, pressure and other parameters in real time. Control stations can be used to maintain constant pressure and regulate the flow of gas.

Intermediate compression stations: At regular intervals along the path, intermediate compression stations can be installed to maintain gas pressure, compensate for pressure losses and ensure a constant flow.

Temperature control: Natural gas may experience temperature variations during transport. Temperature control devices, such as heat exchangers, can be used to prevent condensation or ice formation in gas pipelines.

Arrival and distribution: As natural gas approaches the consumption centres, it is distributed through local distribution networks. These smaller networks serve end users such as households, businesses and industrial facilities.

3.1.2 The LNG carriers

Methane carriers are ships specially designed for the transport of liquefied natural gas (LNG). Their main role is to transport natural gas in liquid form from production or liquefaction sites to consumer markets, usually over long distances and internationally.

Liquefaction of natural gas: Before being transported by methane, natural gas is usually liquefied to reduce its volume and facilitate transport. This liquefaction process cools the gas at very low temperatures, turning it into a liquid.

Storage capacity: LNG tankers are equipped with special tanks to store LNG at extremely low temperatures, typically around -160 degrees Celsius. These tanks keep the gas liquid during transport.

Size and design: LNG carriers vary in size, ranging from small vessels with limited capacity to giant LNG carriers capable of transporting huge quantities of LNG. Their design takes into account the requirements for handling LNG, including extreme temperatures and the need to prevent gas formation inside tanks.

International routes: LNG carriers are frequently used for the international transportation of LNG between production sites and consumer markets. These shipping routes link LNG producers, often far from areas of high demand, to the consumption centres.

Unloading: Upon arrival at their destination, the LNG is discharged by the carriers to dedicated unloading terminals where it is regularly re-gasified before being fed into distribution networks.

Safety: Due to the volatile nature of LNG and the extreme conditions of its transport, LNG carriers are equipped with sophisticated safety features to minimize risks and ensure safe transportation.

LNG carriers play a crucial role in the global LNG trade, facilitating long-range transport of this energy source and helping to meet growing international demand for natural gas

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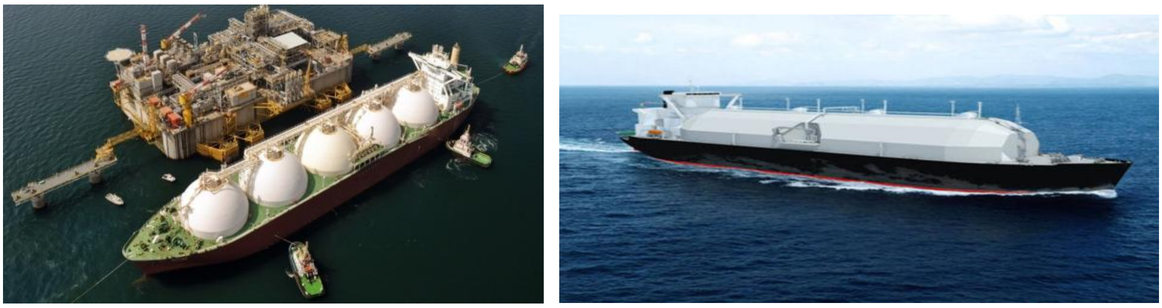


Figure 3. 3 Methane Tankers

Figure 3. 4 Tiger Maanshan, the largest LNG carrier in the world with a capacity of 250,000 dwt (DWT, i.e., 250,000 tons)

3.2 Transportation of oil and petroleum products :

Petroleum is the basic raw material used in the manufacture of fuels for automobiles, aircraft and industrial machinery. Its oil transport can be carried out by different means depending on the distances, destinations, quantities to be transported and available infrastructures. It is carried out mainly by land via pipelines, trains and trucks, or by sea using tankers.

3.2.1 Overland

Pipelines : Pipelines are underground or overhead lines specially designed for the long-range transportation of oil. They provide a cost-effective and efficient way to transport large quantities of crude oil from the oil fields to refineries or export terminals. Pipelines are pipes consisting primarily of steel tubes. These steel tubes are designed to be robust, corrosion resistant and capable of withstanding the high pressures associated with transporting crude oil over long distances. The use of steel helps to ensure pipeline durability and safety. These steel pipes are often buried for safety and aesthetic reasons, although in some cases they may be installed above ground. Steel pipelines are often coated with protective materials, such as special paints or polymer coatings, to create a physical barrier between the metal and the external environment. These coatings help prevent corrosion caused by exposure to moisture, soil chemicals and other corrosive agents.

Pipelines can pass through land or underwater areas.

Figure 3. 5 Onshore Oil Pipelines

Figure 3. 6 Underwater Oil Pipelines At The Bottom Of The Ocean

3.2.2 Rail transport

The transportation of oil by rail is a method used to move significant quantities of crude oil from production areas to refineries or export terminals. Choice of mode of transport depends on various factors such as distance to travel, costs, available infrastructure, local regulations and economic conditions Freight trains, including those carrying oil, have considerable capacity to move large quantities of goods over long distances. Rail transport offers some flexibility in terms of routes, allowing for remote areas or regions without rail infrastructure. Tank cars are specially designed for the transport of liquids, including crude oil. They are equipped with safety devices to minimize the risk of leakage or accidents. The transportation of oil by rail is subject to strict safety standards to prevent accidents and incidents related to the movement of hazardous materials. Although rail transportation is generally considered safe, incidents such as derailments can cause risks to the environment, safety and public health. The use of rail transportation for oil has increased in some regions due to lack of adequate pipeline infrastructure, growing demand for crude oil and market developments.

Figure 3. 7 Wagons-citernes

3.2.3 Trucks

Trucking, also known as road oil transportation, is a common method of moving relatively small quantities of crude oil over relatively short distances. This type of oil transport, which is mainly reserved for already refined products, is usually the final stage in the process of delivery to service stations, reaching end consumers.

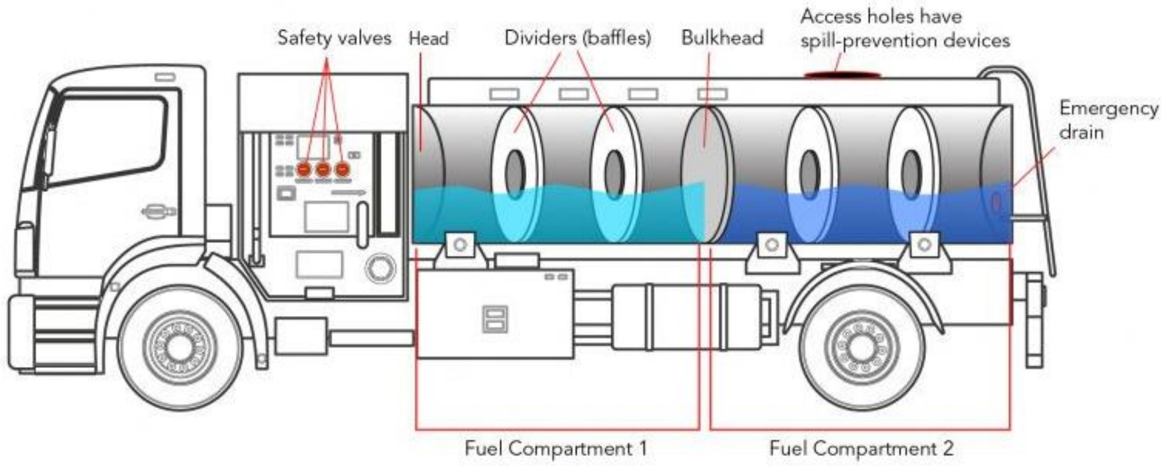


Figure 3. 8 Safety device of a tanker truck

Figure 3. 9 Camion-citerne

3.2.4 Seaway (oil and gas)

Petroleum products, such as crude oil or refined products, may be transported by specially designed vessels, commonly referred to as "tankers" or "supertankers" for the larger of these. These vessels, also referred to by specific terms depending on the type of products transported and their capacity, are tankers dedicated to the transport of oil and its derivatives.

Oil transportation by sea is very flexible, with route paths that can be adjusted. Land transport is still essential, especially for access to countries without direct access to the sea.

3.3 Tankers Types :

Aframax : The Aframax are medium-sized tankers, suitable for the transport of crude oil and petroleum products. They have a capacity between 80 000 and 120 000 tons of deadweight.

Suezmax : These tankers can pass through the Suez Canal and have a load capacity of between 120,000 and 200,000 tonnes of deadweight.

VlCC (Very Large Crude Carrier) : VLC are among the largest tankers and are used primarily for transporting large quantities of crude oil. Their capacity can exceed 200 000 tons of deadweight.

ULCC (Ultra Large Crude Carrier) : The ULCC is the largest tanker, designed to carry massive quantities of crude oil. However, their use has become less common due to port size and operational restrictions.

Figure 3. 10 Tankers

Figure 3. 11 Double-hull tanker

3.4 Coal transport

Since the industrial revolution, coal use has increased significantly. In 1950, coal accounted for 57% of world commercial primary energy consumption. However, this share declined to 27% in 2002 and has remained relatively stable since then, fluctuating between 25% and 31%. The major obstacle to its use is its considerably higher environmental impact.

There are three main categories of coal: peat, lignite and hard coal;

Peat is a fossil organic matter formed by the accumulation over long periods of time of dead organic matter, mainly plants, in a water-saturated medium

Lignite is a sedimentary rock composed of fossil remains of plants (comes from Lignin). It is a rock intermediate between peat and coal.

Coal is a sedimentary carbon rock that comes from the carbonization of plant organisms and can therefore be used as fossil fuel.

Coal is either mined in open pits or underground.

Pit mines are operated in a similar way to quarries, achieving very high recovery rates (90% versus 40% underground) and production costs generally lower than those of underground mines. However, they can also have adverse effects on the environment.

underground mines are equipped with at least two wells to ensure adequate ventilation to evacuate gases and maintain proper air conditioning in the mine. Surface infrastructure is generally arranged around these wells. However, underground mining poses significant safety challenges due to the risks of landslides, firedamp (flammable gas mainly composed of methane) and flooding. In addition, minors are also exposed to lung diseases such as silicosis and pneumoconiosis.

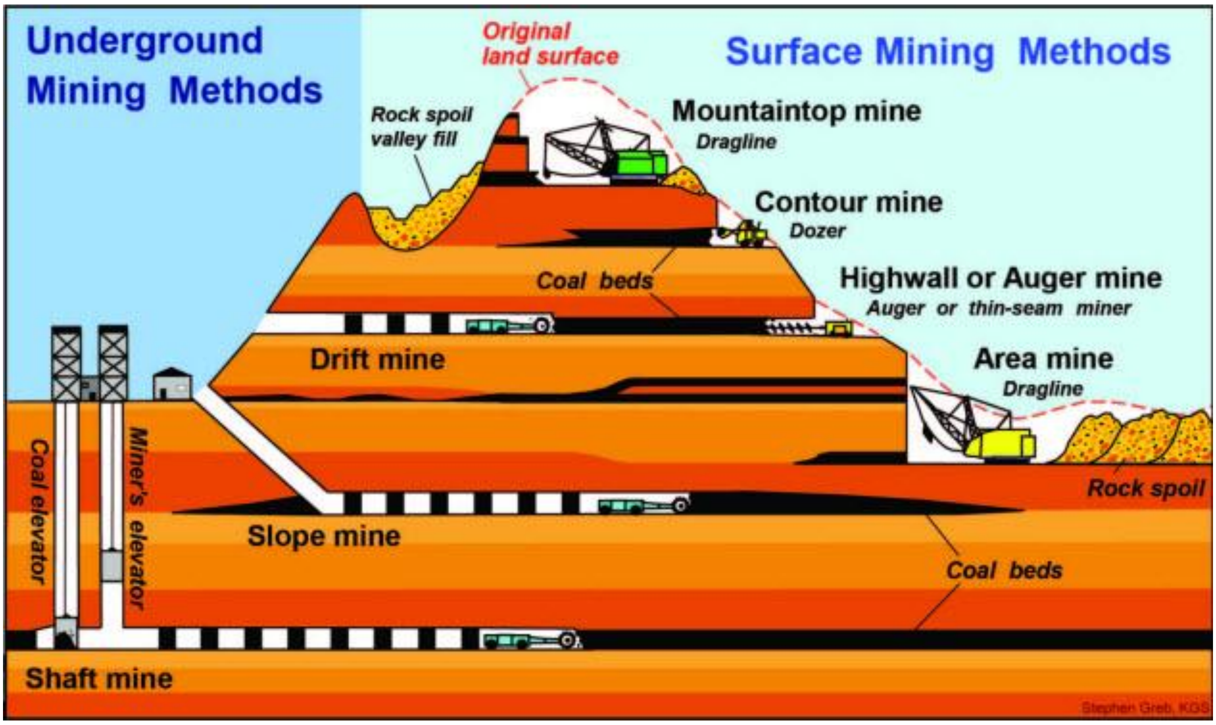


Figure 3. 12 Underground coal mine and right open pit coal mine

Underground coal mine and right-hand open pit coal mine The transport of coal is carried out according to the following common modes of transport: truck transport, rail transport, barge transport, conveyor transport and pipeline transport.

3.4.1 Truck transport

Trucking is a very convenient, fast and flexible way of transport and the quantity of each transport is relatively large. The dumper and side-dump trailers are the most frequently used semi-trailers for coal transport. In some countries where roads are poor and mountain roads are frequently rough, the dumper truck is the most economical way to transport coal.

Figure 3. 13 Dump Truck Trailer

Figure 3. 14 Side dump trailer

3.4.2 Rail transport

Coal transportation by rail refers to the movement of coal from one place to another using railways. This method involves loading coal into specially designed cars and moving it over railway tracks to its final destination. Rail transport often provides an efficient and cost-effective solution for moving large quantities of coal over long distances, particularly between mines and power plants or shipping ports.

Figure 3. 15 Coal-loaded railway train

3.4.3 Barge transport

The transport of coal by barges refers to the movement of coal using barges or riverboats. This method involves loading the coal onto these specially designed vessels, and then transporting them along waterways such as rivers, canals, or streams to their final destination. The coal can be loaded and unloaded at specially constructed docks along the waterways. Transporting coal by barges is often used to move large quantities of coal over long distances efficiently and economically, especially when waterways provide a practical alternative to other land transport modes.

Figure 3. 16 Barge transportation of coal (https://fr.dreamstime.com/transport-du-charbon-barge-%C3%A0-m%C3%A8re-vue-a%C3%A9rienne-navire-image219537707)

3.4.4 Conveyor transportation

Conveyors are used to transport coal from mines to barge terminals, but also directly from mines to power plants, especially if they are nearby. This allows for significant savings. The largest conveyors can transport 2,000 to 5,000 tons per hour. Compared to transport by barge or truck, the conveyor offers the advantage of continuous transport and can easily traverse complex terrain.

Figure 3. 17 Types of conveyors used in coal mines

3.4.5 Slurry pipeline transport

The transportation of coal in slurry form through pipelines involves moving coal suspended in water through pipes. In this method, coal is reduced to a fine powder, mixed with water to form a slurry, and then pumped through pipelines to its final destination. This approach is favored for its efficiency and cost-effectiveness, especially when it comes to transporting coal over long distances between mines and power plants or processing facilities. Slurry pipeline transport of coal offers advantages such as a reduced environmental footprint, improved safety, and superior efficiency compared to other coal transport methods.

3.5 Transport of biomass

Biomass is an organic material derived from plants, animals, or fungi used as an energy source. This energy source can be exploited in three ways:

- directly through direct combustion (wood energy), after the methanization of organic matter (biogas): The principle of methanization consists of fermenting organic matter to transform it into compost, methane, and carbon dioxide. after chemical transformations to create biofuels.

There are different classifications of biomass resources based on their sources:

- wood, in the form of logs, pellets, and chips;
- wood by-products, which include waste generated during forestry operations (such as branches, bark, and sawdust), sawmills (such as sawdust and wood shavings);
- by-products from industry (pulp, waste from agri-food industries (grape and coffee pomace, pulps and grape seeds, etc.));
- products from traditional agriculture (cereals, oilseeds), residues such as straw, bagasse, and new energy crops such as short rotation coppices (willows, miscanthus, etc.);
- organic waste, such as urban waste including sewage sludge, household waste, and waste from agriculture such as agricultural effluents.

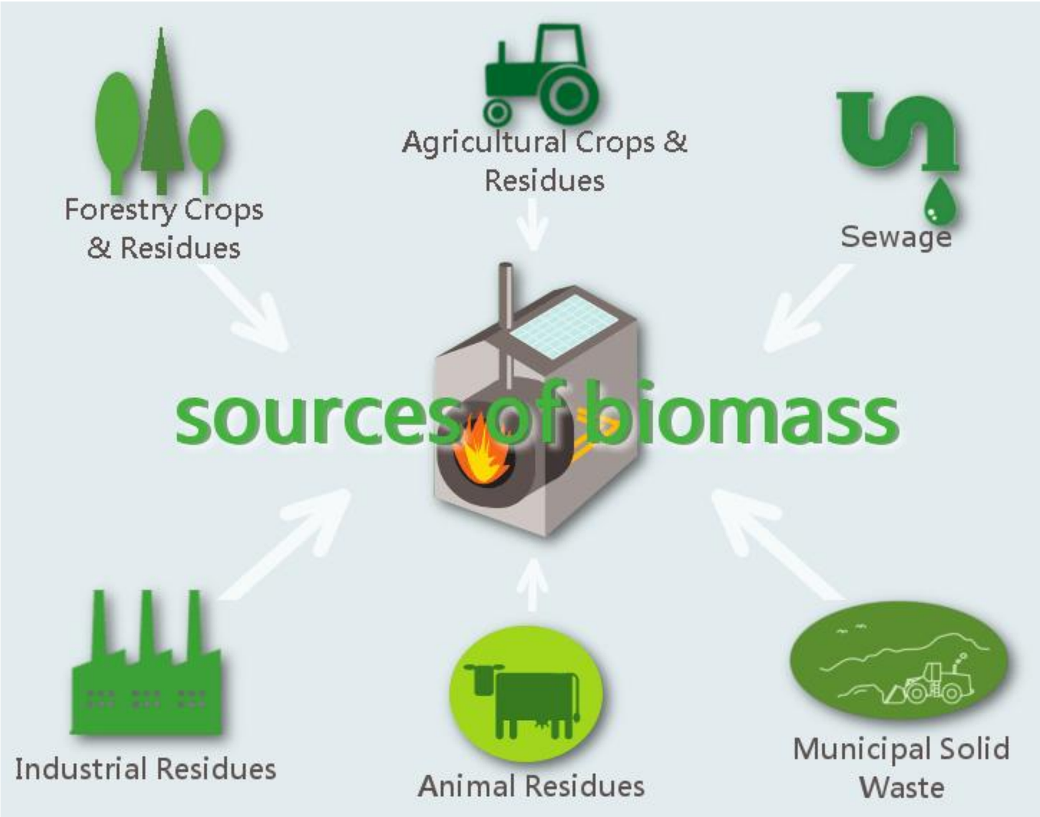


Figure 3. 18 Different source of biomass

The benefits of using biomass are described in the following flowchart:

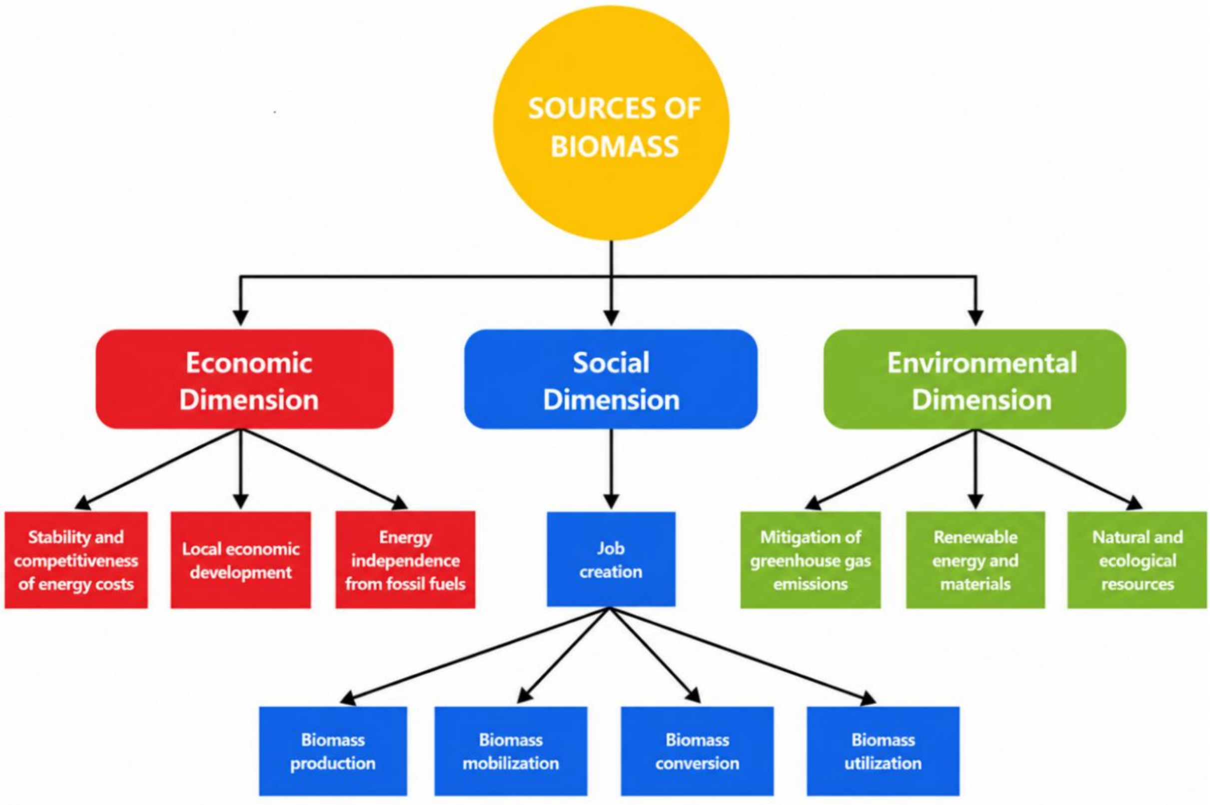


Figure 3. 19 Biomass Sources and Their Impact Across Economic, Social and Environmental Dimensions

There are several ways to transport biomass, depending on its physical form, distance and available infrastructure:

3.5.1 Rail transport:

Trains can be used to transport large quantities of biomass over longer distances. This can be particularly effective for the transport of large quantities of biomass in the form of wood chips or pellets.

3.5.2 Maritime transport:

For coastal areas or large-scale transportation, shipping may be a viable option. Specialized vessels can transport biomass cargo over long distances.

3.5.3 River transport:

In some areas where there are waterways, river transport can be used to transport biomass over long distances efficiently and economically.

3.5.4 Pipeline transport:

Although less common, pipeline biomass transport is a possible option, especially for liquid forms of biomass such as biofuels.

Each mode of transport has its own advantages and disadvantages in terms of cost, efficiency, environmental impact and technical feasibility, and the choice of mode of transport will often depend on these project-specific factors.

3.6 Transport of nuclear fuels

Nuclear fuel is the substance used to produce energy in a nuclear reactor through the fission reaction. These substances are generally fissile, with the most commonly used radioactive metals being uranium-235 and plutonium-239. All the steps involved in the extraction, processing and use of this fuel are grouped into a process known as the nuclear fuel cycle.

Nuclear fuel transport involves the transfer of radioactive materials between different facilities in the nuclear industry, including:

- Transport from the uranium mine to the uranium enrichment plant.
- The transfer from the enrichment plant to the nuclear power plant.
- The movement from the nuclear power plant to reprocessing facilities and/or a storage site for nuclear waste.

The transport of nuclear fuels is a highly regulated and secure process due to the radioactive and *potentially hazardous nature of the materials involved.*

3.6.1 Rail transport:

Nuclear fuels can be transported by train in specially designed and secured containers. These containers are designed to withstand shock, extreme temperatures and radiation protection.

Figure 3. 20 Nuclear fuel transport container

3.6.2 Road transport:

Nuclear fuels can also be transported by truck. As with rail transport, special containers and equipped vehicles are used to ensure the safety of materials and the public.

Figure 3. 21 Transport of nuclear fuel by truck

3.6.3 Maritime transport:

In some cases, nuclear fuels are transported by sea, usually over long international distances. Specially designed and equipped vessels ensure the safe transport of these materials.

3.6.4 Air transport:

Although less common due to logistical and security challenges, air transport of nuclear fuels can be used for emergencies or small shipments. Specially adapted containers and aircraft are used in such cases.

It is important to note that the transport of nuclear fuels is subject to strict regulations, both at national and international level, to ensure the safety of people and the environment. Containers used for transport are designed to withstand a variety of conditions and are rigorously tested to ensure they are robust and capable of containing any radioactive leakage in the event of an accident. In addition, transportation routes are often carefully planned to minimize the risks and potential impacts on people and the environment.

4 Electricity transport :

Electricity is transported through a network of lines and equipment that ensure its transmission, interconnection and distribution. This network ensures that electricity flows efficiently from the place of production to the place of consumption.

The electricity generated is transported from plant outlets over long distances through a network of very high voltage lines, typically between 225,000 and 400,000 volts.

After long-distance transport through the VLA network, electricity is directed to transformer stations. These transformer stations are responsible for converting the very high voltage to high voltage, usually around 90 000 volts, and medium voltage, which is around 20 000 volts.

The medium voltage is then routed to the distribution network. At this stage, it can be converted to low voltage, typically between 230 and 400 volts, before being distributed to end users. The low voltage is then delivered to consumers

4.1 Electricity networks

An electrical grid is a complex system of infrastructure designed to transport electrical energy from production centres to consumers. It consists of power lines operating at different voltages, interconnected in electrical substations. These substations are used to distribute electricity and convert it from one voltage to another using transformers. In addition, an electricity grid must ensure dynamic management of production, transport and consumption by implementing adjustments to maintain the overall stability of the system.

In the context of the organization of electric energy transmission, two categories of electrical networks stand out: transmission networks and distribution networks.

The transport network

The transmission network consists of two categories of lines: very high voltage (HTB2) and high voltage (HTB).

HTB2 lines are designed to transport large amounts of electricity over long distances while minimizing losses. They have a voltage greater than 100 kilovolts (kV) and form the large transmission or interconnecting network. These lines connect different regions and countries with each other and feed directly into large urban areas. Most HTB2 lines have voltages of 400 kV and 225 kV.

On the other hand, HTB lines constitute the regional distribution or supply network, allowing transport at a regional or local level. They supply electricity to heavy industries, large consumers such as rail transport and provide the connection to the secondary network. Their voltage is generally 63 or 90 kV.

4.2 Technical Components of Electricity Transmission

Electricity transmission systems rely on several technical components that ensure the safe and efficient transport of electrical energy over long distances. These components mainly include transmission towers, conductors (cables), insulators, and underground transmission systems.

4.2.1 Transmission Towers (Pylons)

Transmission towers, also called pylons, are metallic structures used to support overhead power lines. Their main function is to maintain sufficient distance between conductors and the ground in order to ensure safety and reduce electrical risks.

Several types of pylons are commonly used depending on the voltage level and geographical conditions:

- ✓ **Suspension towers:** used on straight sections of transmission lines.
- ✓ **Tension towers:** designed to withstand higher mechanical forces at line angles or terminal points.
- ✓ **Guyed towers:** stabilized using tensioned cables to reduce structural weight.

The height of pylons generally increases with transmission voltage to maintain electrical insulation and safety distances.

4.2.2 Types of Electrical Cables

Electrical energy is transported through conductors made mainly of aluminum or copper due to their high electrical conductivity.

The most common conductor types are:

- ✓ **AAC (All Aluminum Conductor):** lightweight and economical.
- ✓ **ACSR (Aluminum Conductor Steel Reinforced):** reinforced with a steel core for improved mechanical strength over long distances.
- ✓ **Underground insulated cables:** protected by insulating materials and used in urban or sensitive areas.

The choice of cable depends on several factors such as transmission distance, current capacity, mechanical resistance, environmental conditions, and installation cost.

Figure 2. 4 High voltage electric pole and transmission lines. Electricity pylons. Power and energy concept

4.2.3 Underground Transmission Lines

In densely populated urban areas or environmentally sensitive regions, underground transmission lines are increasingly used instead of overhead lines.

These systems offer several advantages:

- ✓ Reduced visual impact,
- ✓ Improved public safety,
- ✓ Better protection against weather conditions,
- ✓ Lower electromagnetic exposure in surrounding areas.

However, underground lines are generally more expensive to install and maintain because of excavation work, insulation requirements, and cooling constraints.

4.2.4 Insulators and Protection Equipment

Insulators are essential components that electrically isolate conductors from pylons and prevent current leakage. They are usually made of:

- ✓ Porcelain,
- ✓ Glass,
- ✓ Composite polymer materials.

Additional protection equipment such as circuit breakers, lightning arresters, and grounding systems are also used to ensure network reliability and protect installations from electrical faults and lightning strikes.

Figure 2. 5 High voltage equipment to supply electricity.

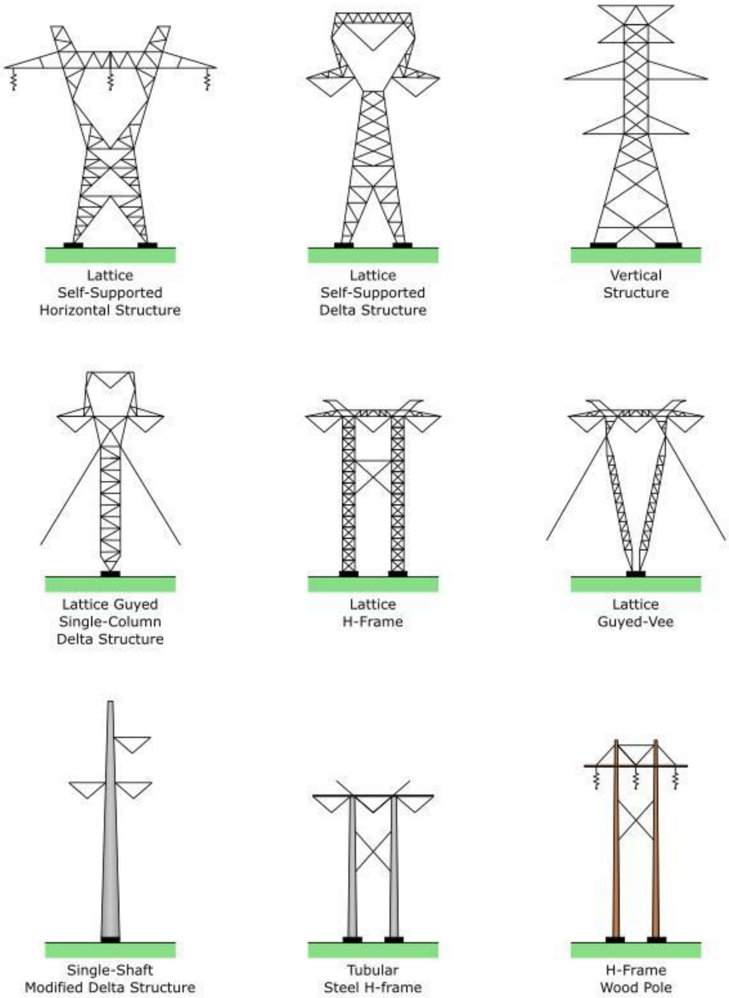


Figure 2. 6 Transmission Tower Types. Source (https://savree.com/en/encyclopedia/electrical-transmission-towers?utm_source=chatgpt.com) accessed on 08/12/2025

4.2.5 The distribution network

The distribution network consists of two types of lines: medium voltage (HTA) and low voltage (BT) lines.

HTA lines provide local electricity transmission to small industries, SMEs and local businesses. They also establish the connection between customers and processing stations. These lines operate with a voltage between 15 kV and 30 kV.

As for the BT lines, they are the smallest of the network and operate at a voltage of 230V or 400V. They play a crucial role in the distribution of electrical energy to households and artisans, thus providing daily power for our household appliances.

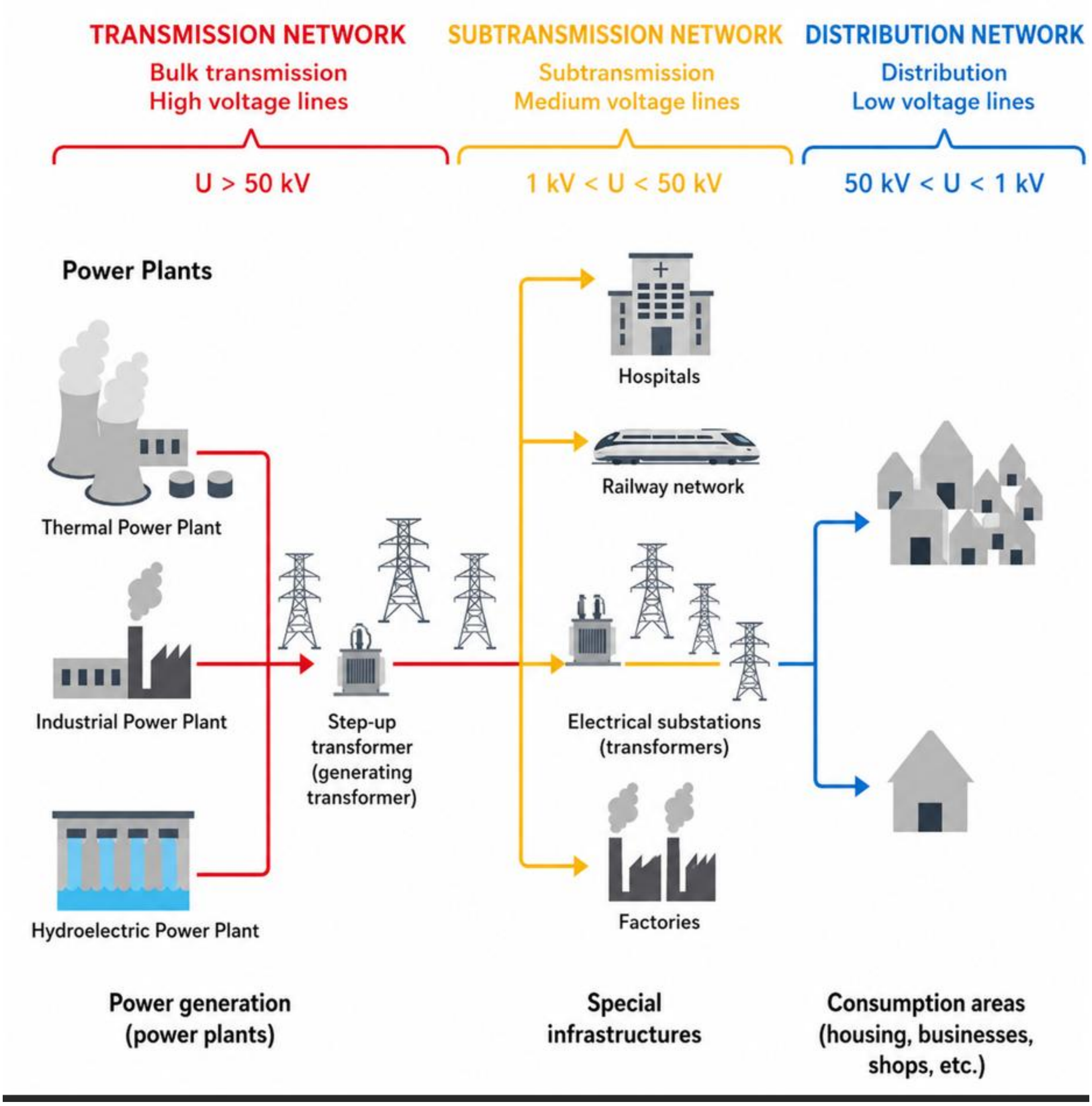


Figure 3. 22 Electricity transmission network: from production to consumption

5 Hydraulic power transmission

Water power is generated by the movement and force of water, whether it be rivers, waterfalls, waves or sea currents, and is a renewable source of electricity. The movement of water is used to drive a turbine, which in turn turns an alternator, thus producing an alternating electric current. The amount of energy produced depends on the intensity of the movement of the water that drives the turbine. This energy is considered the most important renewable energy source.

Hydroelectric power plants can be classified into three main types according to their functionality and location:

5.1 The hydropower plant of diversion, or "on the run-of-the-water":

It is highly dependent on weather and river flow because it does not have water storage capacity. It uses circulating water to generate energy. These plants are often smaller and less adaptable to electricity demand. However, they preserve the natural course of the river, which reduces their environmental impact.

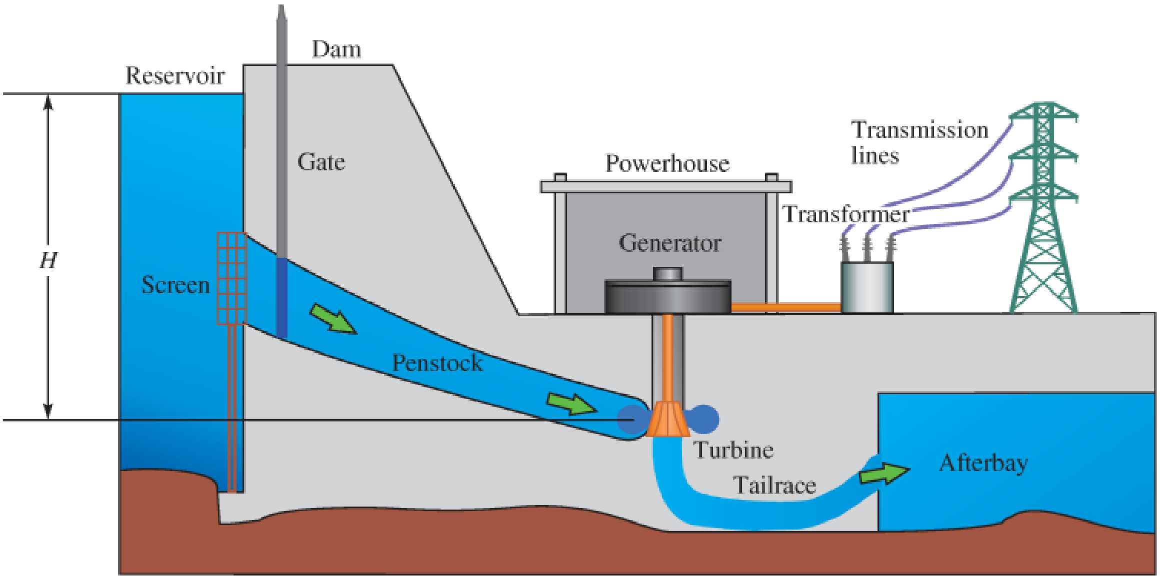


Figure 3. 23 The operational diagram of a low fall power plant, also known as "water line" power plant

5.2 The Reservoir Hydroelectric Power Plant:

It relies on the storage of water in different quantities to regulate its production according to the electricity demand. These power plants operate as large semi-natural energy batteries, meeting society's energy needs as long as water resources are available.

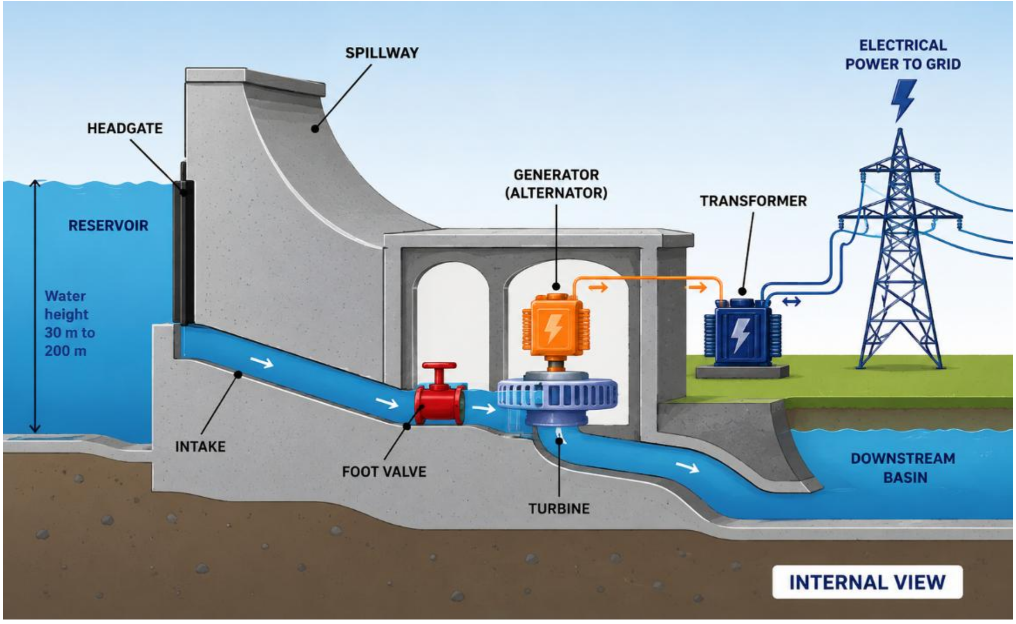


Figure III. 1 The operating scheme of a medium-fall power plant

- In a high fall power plant, the principle is to exploit the potential force of water stored in dams, based on the same principle as a waterfall to generate electricity. The larger the waterfall, the greater the impact force at the bottom. The installation therefore simulates a cascade by placing turbines at the very bottom, where the maximum force is. This facility is divided into three distinct parts::
- dam
- Forced Pipe
- The turbines

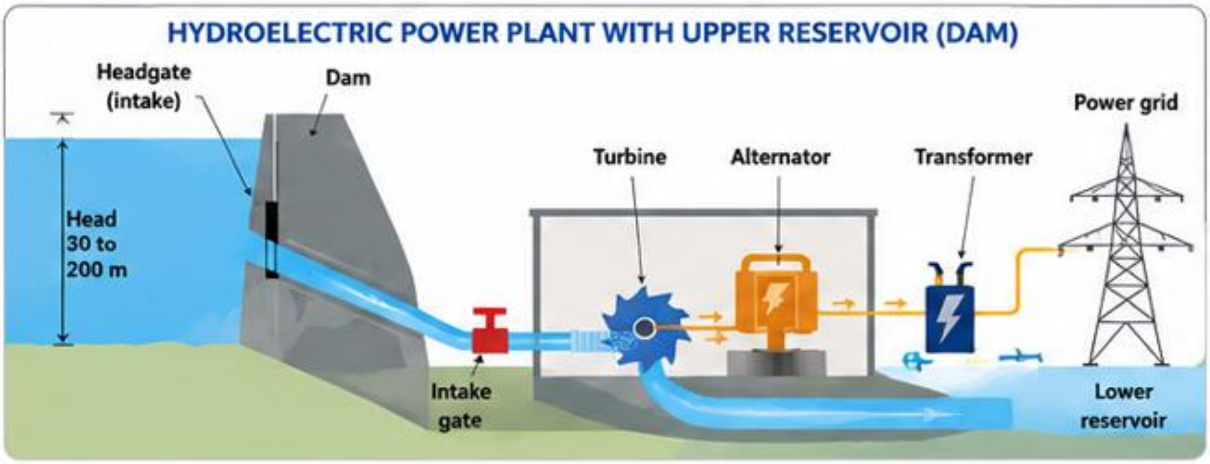


Figure 3. 24 The operating diagram of a high-fall power plant

6 Thermal energy transport:

Electricity is difficult to store and easily transported, whereas heat is more easily stored but its transport is more difficult.

The transmission of thermal energy from source to user can be achieved in different ways, depending on specific needs and environmental conditions and especially the location of heat producers and its users. However, long-distance energy transport is a real challenge.

To improve the efficiency of the dimensioning and operation of a heat network, the use of a thermal storage unit is an efficient method. It stores heat when generated by a facility during periods of low demand and then releases it when there is high demand. There are currently many heat storage techniques, some already proven and others in the process of industrial validation.

Since the 2000s, technologies have been developed and are being developed for long-distance transport. They have been specifically designed to manage residual thermal energy or heat waste, particularly for domestic heating or air conditioning.

These technologies include:

• reversible chemical reactions,

• Phase change based latent heat storage,

• transportation by vehicles or pipelines,

• the use of hydrogen-absorbing alloy,

• chemical adsorption solid-gas, • liquid-gas absorption,

• etc......

The transmission of thermal energy from source to users depends on two essential factors:

- Thermal level:
    - o low temperature: district heating networks
    - o high temperature: industrial application
- Energy form transported => energy vectors:

✓ Sensitive heat

✓ latent heat

✓ reaction heat

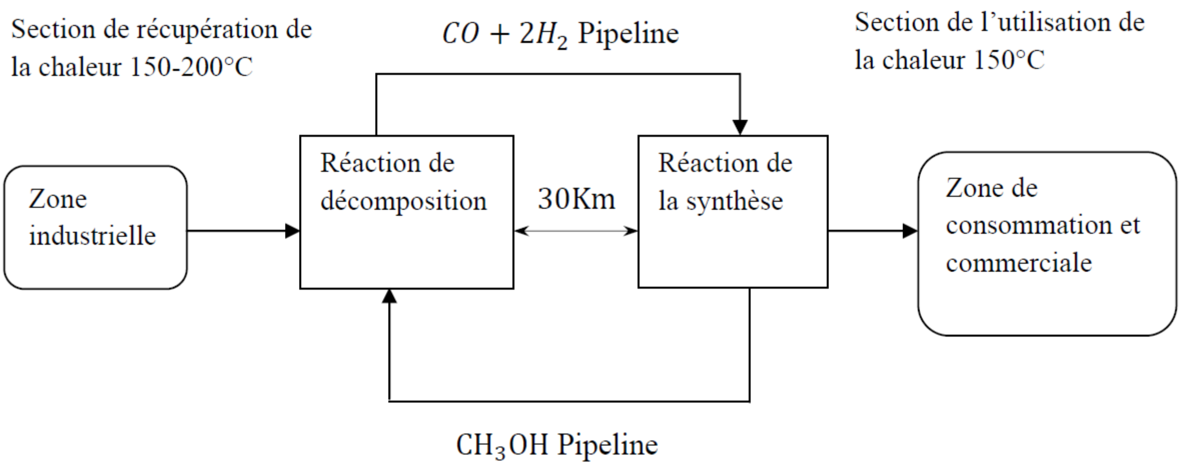
6.1 Thermal energy transport by chemical reaction

Reversible chemical reactions are often preferred for high temperature thermal energy transport. For low temperature storage, however, methods such as phase change based sensitive heat storage, hydrogen absorbing alloys, solid-gas adsorption and liquid-gas absorption are more suitable.

Reversible chemical reactions of methanol, such as synthesis and decomposition, can be exploited to transport heat from waste. As a means of transport, methanol is considered the most suitable solution due to its excellent properties, including decomposition temperature, purity and affordability. The chemical reaction of methanol decomposition is represented as follows:

$$\mathrm{CH_3OH} \Leftrightarrow CO + 2H_2 + \Delta H_{298K} = 95KJ/mol(CH3OH)$$

With ΔH_{298K} is the amount of thermal energy from methanol decomposition.



6.2 Sensitive heat transport by pipelines

Commonly applied in district heating for low temperatures.
A district heating system consists of a large boiler room and a network of pipes distributing a heat-transfer fluid, usually water, to the radiators in the dwellings served. Substations with meters are installed in buildings to facilitate heat transfer.

The most widely used coolant is water:

Hot water: Used mainly in networks where heat generation systems operate at low temperatures, such as geothermal. Its maximum temperature is generally between 100 and 110°C.

Superheated water: It is the most commonly used fluid in district heating. Installations can be classified into two categories according to the temperature of the fluid:

Relatively low temperature facility: The fluid typically reaches a maximum temperature of 120 to 140°C at departure.

High temperature installations: In this case, the fluid is heated to temperatures ranging from 180 to 210°C at the outset.

A conventional heat network consists of three main elements:

The boiler room: This is the site where heat is produced to supply the network. Although there may be several boiler rooms in the same network, their number remains limited.

The transport and distribution pipelines: These are conduits that carry heat using a heat transfer fluid, usually liquid water, sometimes in the form of steam.

The substations: These are the delivery points of heat, serving as an interface between the district heating network and the serviced buildings. Downstream of the substations, there may be so-called "secondary" distribution networks, often integrated into the buildings' installations rather than the main district heating network.

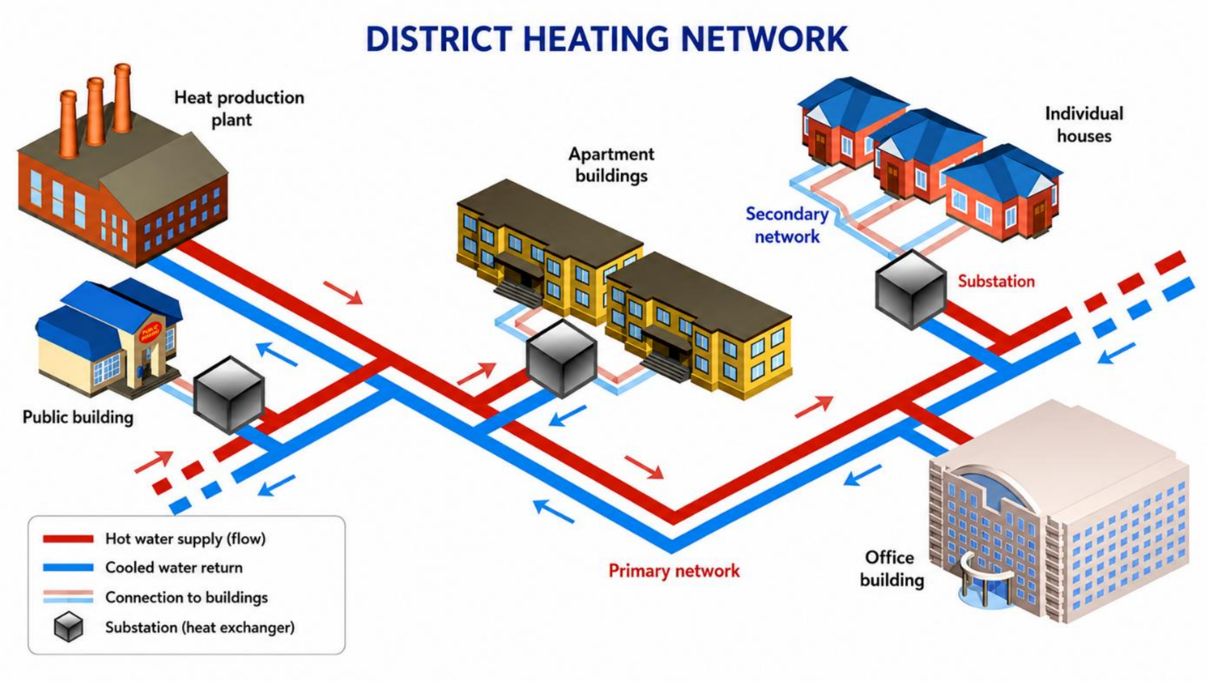


Figure 3. 25 District heating networks, source (https://www.notre-environnement.gouv.fr/actualites/breves/article/les-reseaux-de-chaleur-une-solution-pour-decarboner-le-chauffage)

This heat transport system has some advantages and disadvantages.

Avantages :

- Performance and profitability
- Safety: The presence of local authorities supervising the system ensures enhanced security and minimizes the risk of malfunctions.
- Comfort and convenience for users: Users can enjoy heating without problems, without the need to maintain the device or find a suitable location in their home
- Exploitation of local resources
- Low greenhouse gas emissions and air quality preservati

The disadvantages:

- High investment for the city during the construction of the structure
- System suitable only for densely populated areas to limit the length of pipelines and reduce heat losses
- Installation and maintenance work can cause disruptions in the city, particularly regarding road traffic

6.3 Heat transport by latent heat

The use of phase change materials (PCMs) in the transport and storage of thermal energy is a promising technology in the field of renewable energy and energy efficiency. PCMs are materials capable of storing large amounts of energy in the form of latent heat when they change from one phase to another, for example from solid to liquid or vice versa.

Phase change material fusion (PCM) stores thermal energy as latent heat. This stored heat can be loaded into tank containers and easily transported by trucks, trains or ships. To recover this latent thermal energy, the PCM undergoes a solidification using a heat transfer fluid such as oil or a nano-fluid. The thermal energy resulting from the solidification process can be used for various purposes, such as heating of water for residential use.

The use of phase change for heat transport offers several advantages:

- flexibility, in particular;
- high yield,
- a stable heat supply.
- In addition, it contributes to the conservation of fossil fuels and the reduction of CO_2 emissions.

Finally, the following figure summarizes all forms of energy transport::

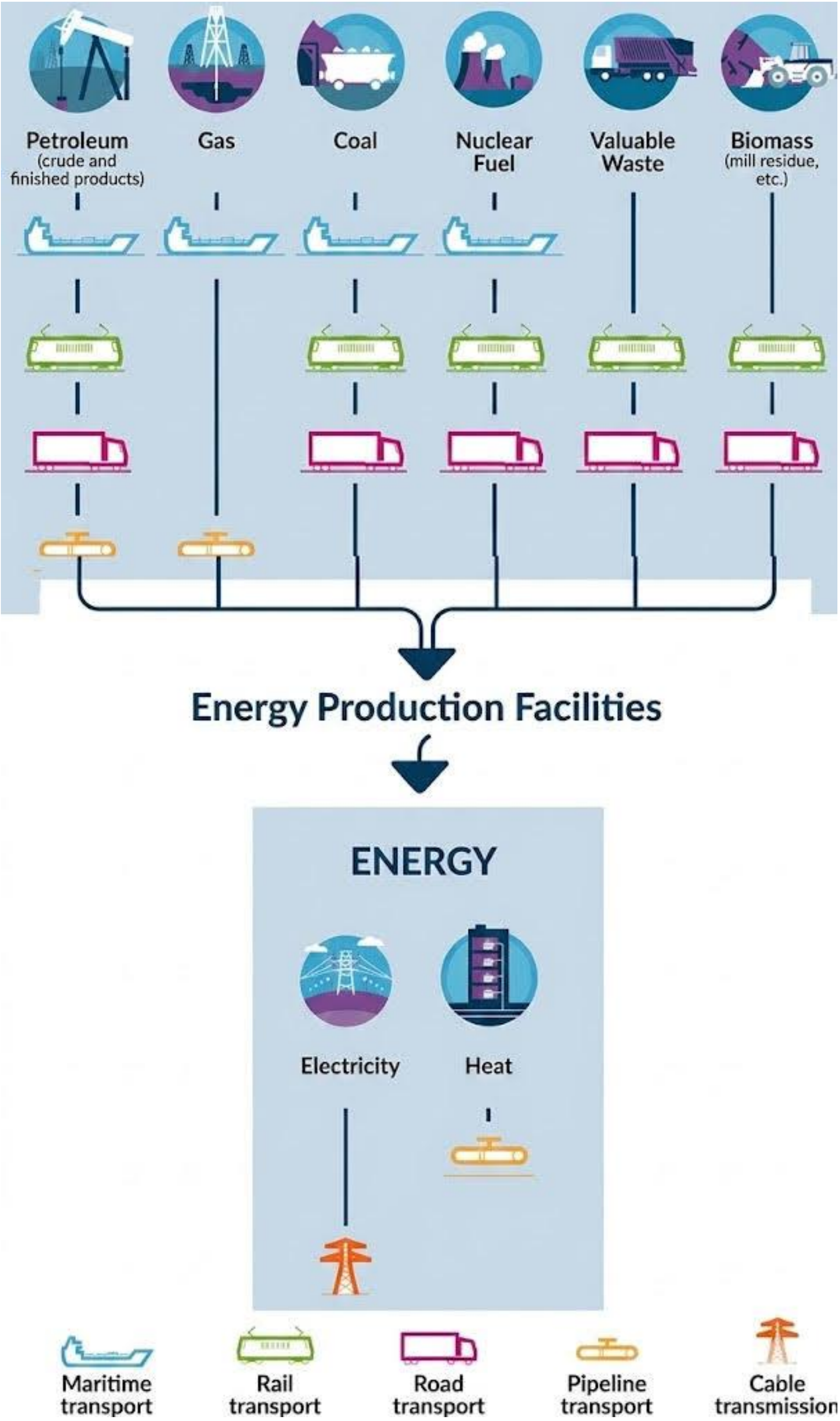


Figure 3. 26 Different modes of transport for fuels and energy

7 Conclusion

This chapter presents the different modes of energy transmission, illustrating the complexity and diversity of energy transmission mechanisms. From fuels to electricity, hydro and thermal power, we have explored the main infrastructures and technologies that allow the delivery and distribution of energy resources in our systems.

1 Introduction

Energy storage is to reserve a quantity of energy for later exploitation. Its objective is to maintain a balance between energy production and consumption, minimize losses and rationalize costs. So it is a process that allows an adaptation between supply and demand over time. Its main function is summarized in three essential points:

Need for autonomy: it is the ability to carry its own energy reserve

The need to compensate for the time lag between energy demand and production availability

The need to correct fluctuations in the current supplied on the power grid. This applies, for example, to wind turbines or solar systems.

The need for storage arises from various economic, environmental, geopolitical and technological considerations.

Following this introduction, this chapter provides an overview of the main energy storage technologies, including mechanical, electrochemical, chemical, and thermal storage systems. The chapter also discusses the principles of operation, advantages, disadvantages, efficiency, and applications of each storage method, with particular emphasis on their role in modern energy systems and the energy transition.

2 Energy efficiency of an energy storage

Energy efficiency of an energy storage refers to the extent to which stored energy is conserved and used efficiently when recovered from the storage system. This involves minimizing energy losses during the storage and release process, to ensure that as much stored energy as possible is available for future use.

3 Forms of energy storage

Energy storage varies according to its type. Fossil energy sources such as coal, gas and oil are naturally natural reservoirs, making them ideal for storage. Once extracted, these energy sources can be easily isolated, housed and transported. However, the storage of intermittent energy presents a greater challenge. These types of energy, which depend on energy carriers such as electricity, heat or hydrogen, require specialized storage systems to ensure continuous supply.

Figure 4. 1 summarizes the different energy storage solutions.

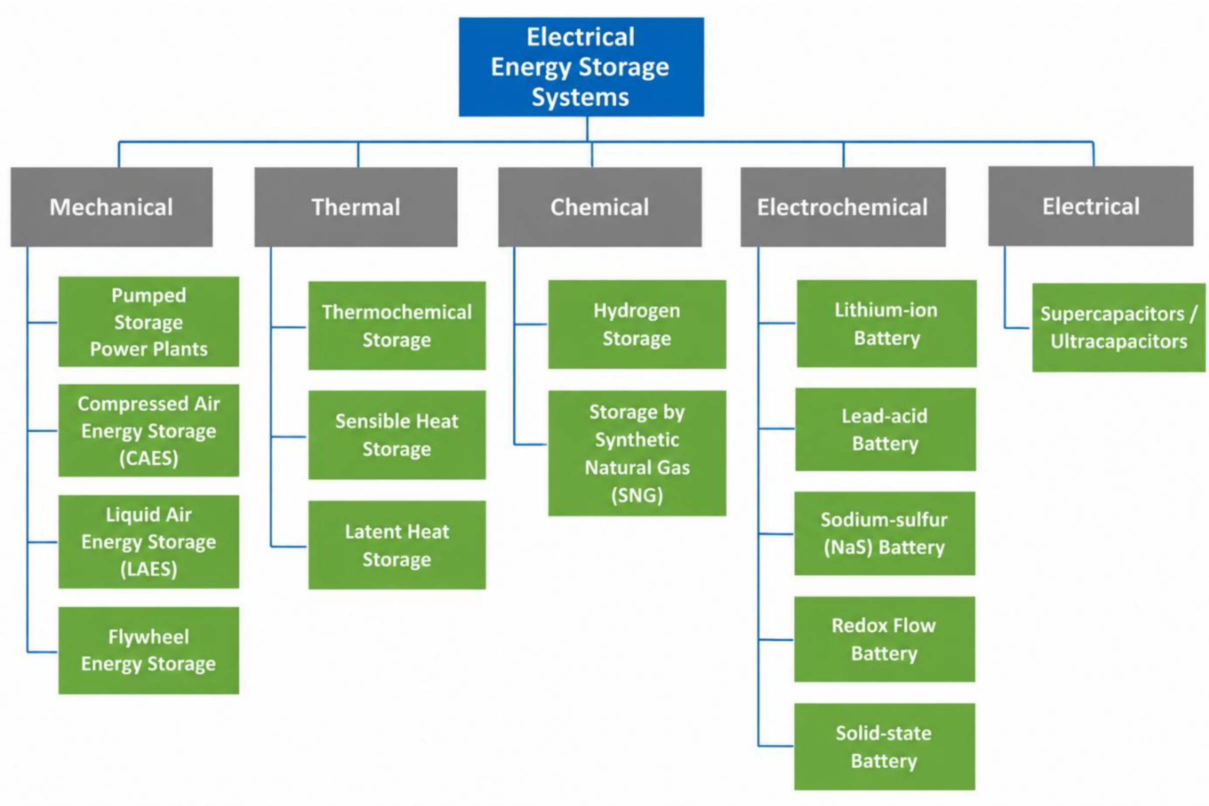


Figure 4. 1 Main energy storage technologies (Worku et al., 2022)

3.1 Mechanical storage

This category encompasses the most familiar methods of large-scale energy storage.

3.1.1 Potential mechanical energy

It is storing energy through the potential energy of water. Water dams are reservoirs of water that, when they fall, turn turbines generating electricity. System optimization involves reusing the water that has been released. Pumped storage is used in some places to equalize the daily load.

The potential energy of water is used to store large quantities of electrical energy. To facilitate this process, a hydroelectric power plant known as PETS (pumped storage station) is used. This station transfers water between two basins located at different altitudes. During periods of excess electricity in the system, water is pumped from the lower basin to the upper basin. Gravity turns this water body into a reservoir for future electricity generation. Conversely, in the event of a shortage of electricity production, the flow of water reverses: the pump is transformed into a turbine and releases the stored energy. With an impressive efficiency of over 80%, this method is the most commonly used solution for energy storage in power plants.

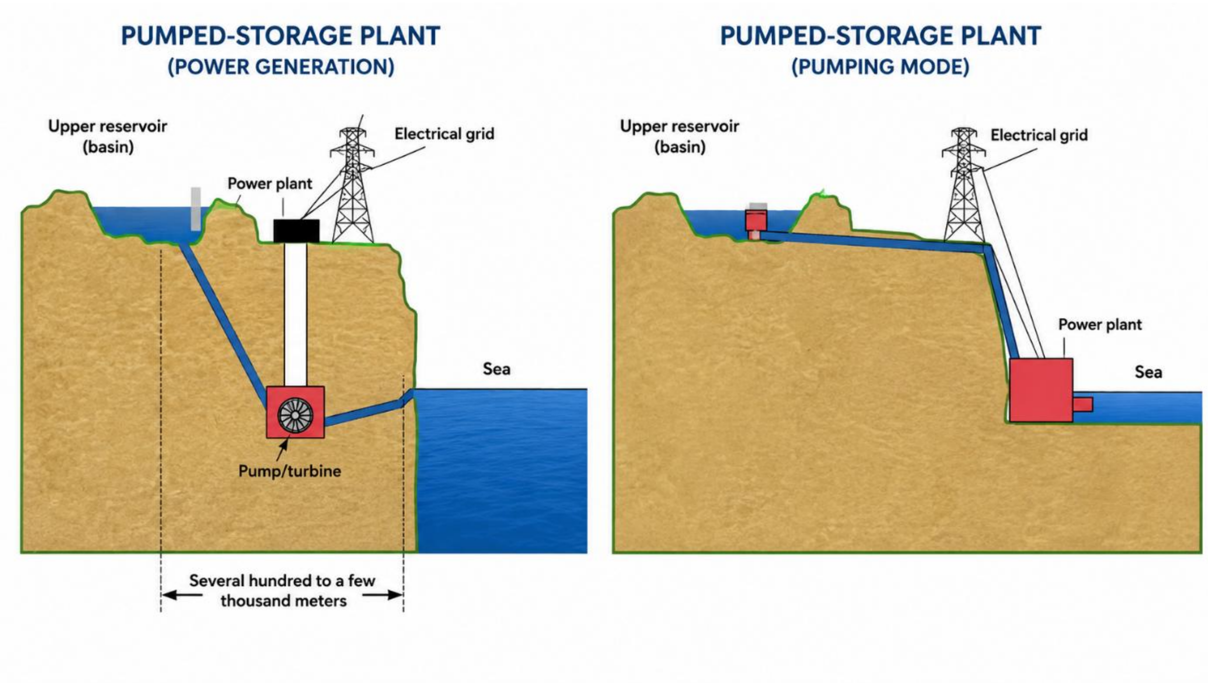


Figure 4. 2 Operation of a source gravity facility. Source: adapted from (https://sti2d.ecolelamache.org/stockage_de_lnergie_lectrique.html) accessed May 23, 2025

3.1.2 Compressed air storage

It is an underground storage of compressed air that is part of the stationary energy storage solutions on a very large scale This particular method of storage involves the use of excess electricity, even from wind turbines or solar installations, generated during periods of low demand to compress air at extremely high pressure and store it in an underground reservoir of various geological formations (old mines, salt, porous rock, aquifer). When demand is at its peak, stored potential energy is exploited by releasing compressed air through a turbine, which in turn drives an alternator to generate electricity.

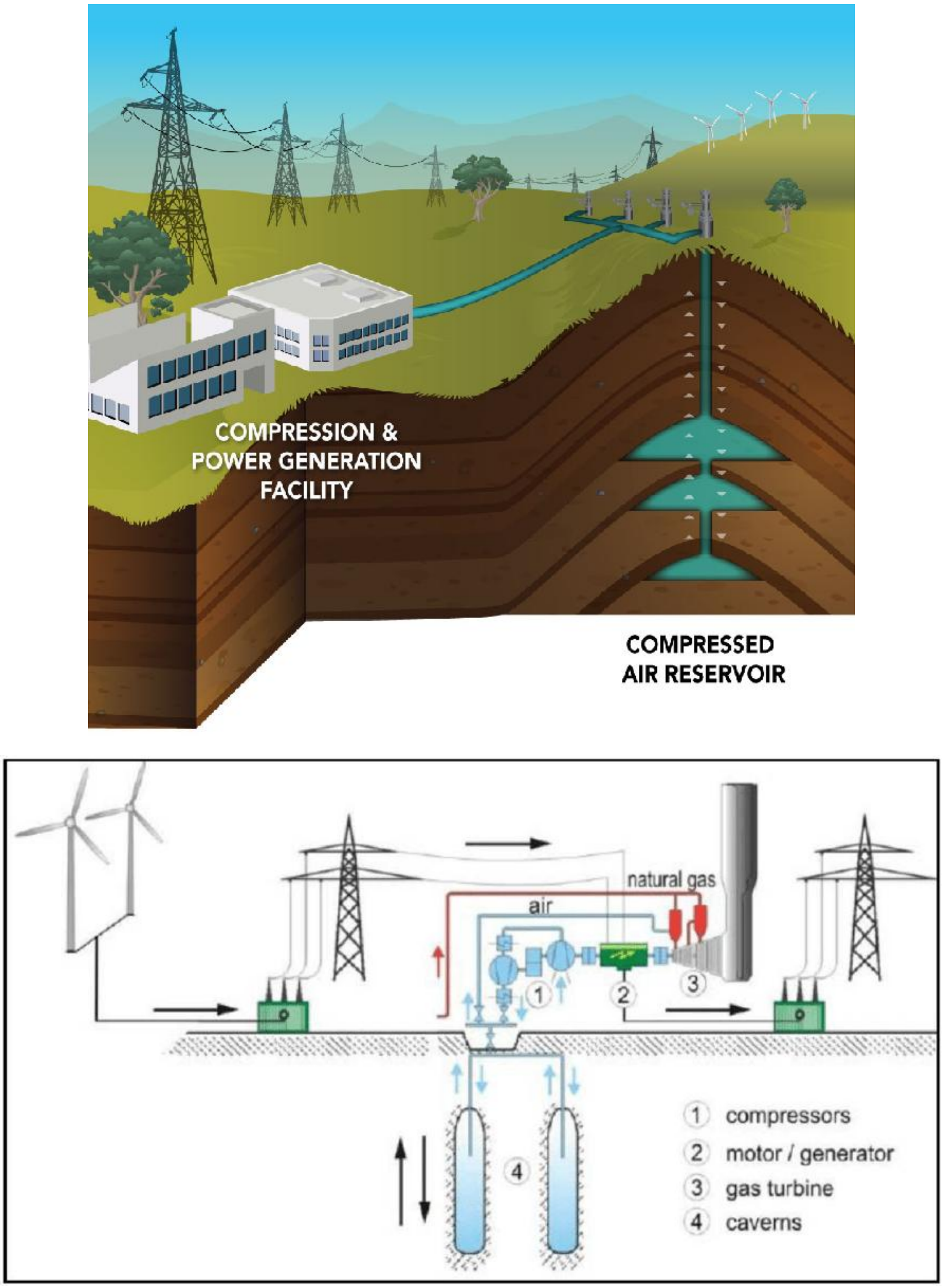


Figure 4. 3 : Schematic diagram of the Huntorf power plant: Top image adapted from (https://newenergyandfuel.com/http:/newenergyandfuel/com/2013/05/21/wind-compressed-air-and-geothermal-hybrid-energy-storage/) accessed May 23, 2026 ; bottom image reproduced from (Ghoreyshi & Schobeiri, 2015).

The theoretical quantity of stored mechanical energy E is calculated by:

$$E = V \Delta p$$

Where V is the volume of gas and Δ p is the pressure difference between the atmosphere and the tank.

Advantages and disadvantages

The advantages of this technique are numerous: :

- Reduced cost;
- No pollution from air emissions and leaks;
- Adaptability in explosive environments;
- Built-in cooling capacity;
- Robustness to temperature variations, especially in industrial environments such as forges and foundries;
- Vibration resistance;
- Increased safety compared to direct use of electricity..

Despite its advantages, this method also has some disadvantages:

• Difficulty in maintaining constant power due to compressibility of air and pressure fluctuations during expansion;

• Noise generated by air emissions;

• Operational cost

3.1.3 Kinetic mechanical energy

The flywheel is a component that stores and returns electrical energy in the form of kinetic energy. This device has many advantages: low sensitivity to temperature changes, long autonomy and life.

Energy storage by flywheel allows the temporary storage of energy in the form of mechanical rotation.

Energy can be temporarily stored as kinetic energy in a device called “flywheel” that rotates around its central axis. In this system, an electric machine supplies the flywheel with kinetic energy (motor operation) and recovers it as required (generator operation), which results in a decrease in the rotational speed of the flywheel. Although this system allows more than 80% of the stored energy to be returned, its storage capacity is limited in time. In practice, the flywheel is used for very short-term smoothing of energy supply within production equipment, especially in thermal engines and especially diesel engines.

A modern flywheel is made up of a mass, often disc-shaped, ring or cylinder, driven by an electric motor. The theoretical stored energy E is proportional to the square of the rotational speed ω and the moment of inertia of the flywheel:

$$E = \frac{1}{2}\ \omega^2 I = \frac{1}{2}\omega^2 \iiint R^2 d\, m$$

Where I is the moment of inertia and ω is the rotational speed in radians per second, dm a mass element located at a distance R from the centre of rotation. The integral covers the entire volume of the flywheel.

The electrical energy supplied allows the steering wheel to be accelerated to very high rotational speeds, ranging from 8,000 to 16,000 revolutions per minute, in just a few minutes. Once rotated, the mass continues to rotate even in the absence of power supply.

To optimize the device's performance, that is to reduce friction, which increases the rotation time and prolongs the storage time, the system is mounted on magnetic bearings and placed under vacuum in a protective enclosure.

This system has several advantages:

1. High efficiency: About 80% of the energy absorbed can be returned, making it an efficient system.

2. Fast storage phase: Compared to an electrochemical battery, the storage time is very short, which allows a quick response to energy needs.

3. Short response time: This speed allows for efficient regulation of the frequency of the electrical network.

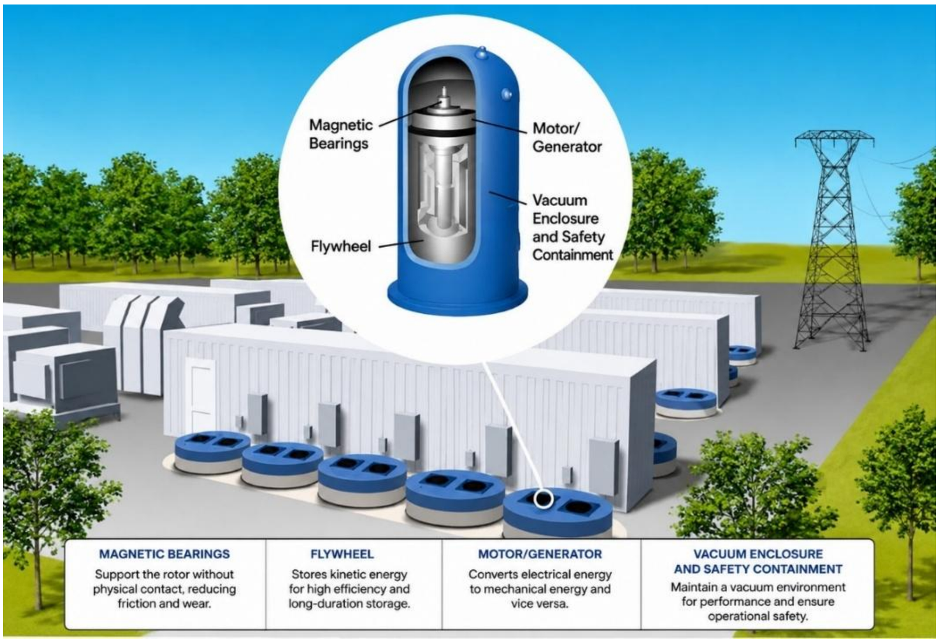
4. No pollution: No fossil fuels or chemicals are used, ensuring an environmentally friendly system.

5. Reliability and low maintenance: The technology is reliable and requires little maintenance, ensuring high system availability.

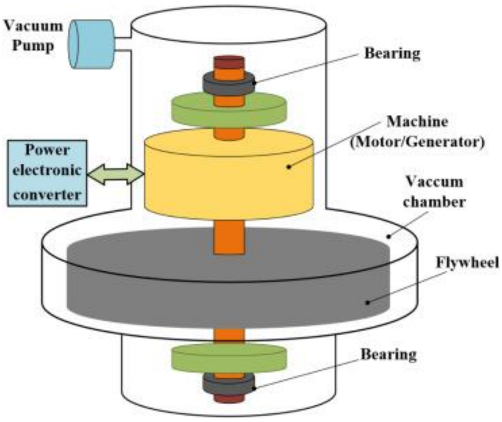
Its disadvantages are:

1. Limited storage time: The storage time is limited to approximately 15 minutes. This short time can be a disadvantage for applications requiring longer energy reserve.

2. Limited autonomy: Unlike electrochemical batteries or energy storage by pumping/turbining, the energy storage by flywheel does not allow to obtain an extended autonomy. This may limit its use in applications requiring extended battery life.



(a)



(b) (c)

Figure 4. 4 : Storage by flywheel: (a) source (https://www.actu-environnement.com/ae/dossiers/stockage-electricite/panorama-technologies.php?utm_source=chatgpt.com) accessed on 23/05/2025 (b) (Zhang, Wang, Liu, & Tian, 2022); (c) source (https://fr.energydawnice.com/flywheel-energy-storage/)) accessed on 13/04/2025

An inertial flywheel is a system for storing energy in the form of rotational kinetic energy. It is made of a mass, mostly a hollow or solid cylinder (but other forms are possible). This mass is rotated around an axis, which is generally fixed, and enclosed in a protective enclosure. It is connected to an electric motor/generator that converts kinetic energy into electricity and vice versa.

This mechanism allows energy storage:

- In the storage phase, the motor converts incoming electrical energy into kinetic energy, which increases the rotation speed of the mass;
- in the stationary phase, that is to say, in the energy conservation phase, the rotation speed of the mass must be maintained constant. The energy input is minimal and only compensates for friction losses;
- During the de-stocking or return phase, the generator converts mechanical energy into electricity, thus braking the mass.

3.2 Electrochemical and electrostatic storage

Electrochemical and electrostatic storage are two distinct approaches to storing electrical energy, each with its own principles and applications.

3.2.1 Electrochemical storage:

This type of energy storage involves chemical reactions that occur between electrodes and an electrolyte in an electrochemical cell, such as a battery or battery.

When the cell is discharged, stored chemical energy is converted into electrical energy to power a device or device. Electrochemical batteries are often characterized by their electric charge q in ampere-hours. If the operating voltage U is known, the stored electrical energy is then:

$$E = q\,U \text{ en Watt-heure ou } E = 3600\, q\, U \textit{ en joule}$$

This storage system is used by batteries, which store energy through reversible electrochemical reactions. When these reactions are not reversible, they are called single-use batteries. Their operation is based on the difference in electrical potential between two ion-conducting materials forming electrodes. These materials are selected in such a way that a reversible redox reaction can be established. The electrons exchange through an external electrical circuit, while an ion exchange through an electrolyte balances the reaction internally. The battery is discharged as both electrodes transform, making the reaction impossible in time. To recharge the battery, an inverse electrochemical reaction is initiated by circulating a counter current between the electrodes.

Rechargeable batteries, such as lithium-ion batteries, lead acid batteries and nickel-cadmium batteries, are common examples of electrochemical storage.

This type of storage is widely used in mobile applications, such as electric vehicles, portable electronic devices and home energy storage systems.

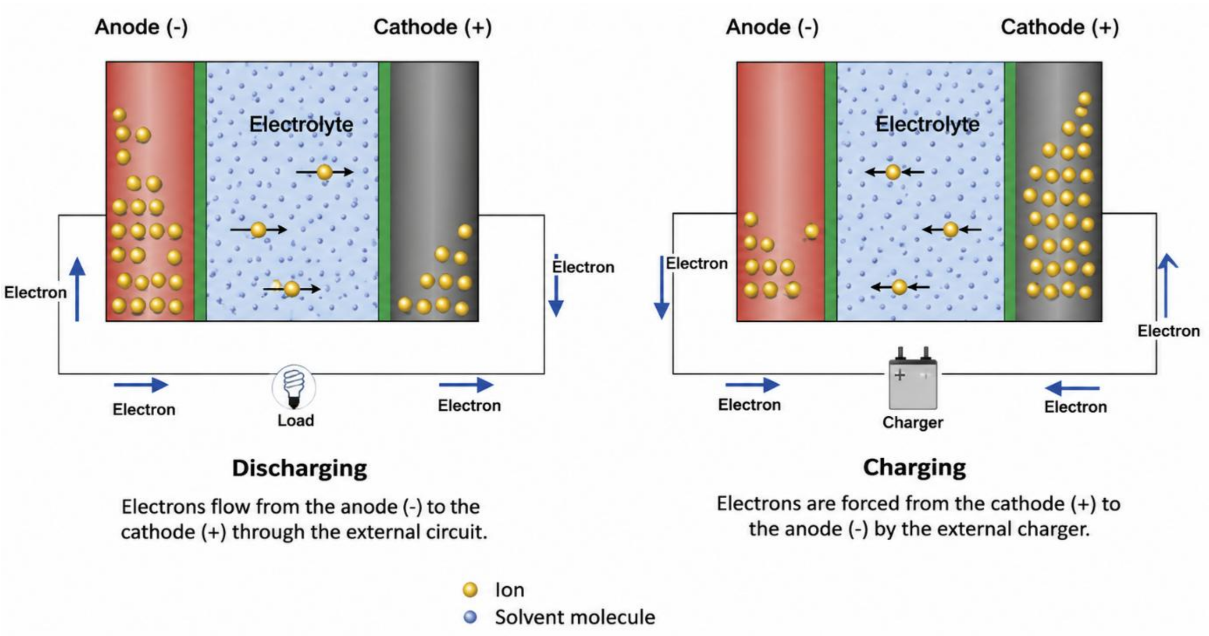


Figure 4. 5 Electrochemical reactions in a battery under charge or discharge

Do not confuse a battery, a rechargeable battery, an accumulator and a battery:

• A battery stores electricity, but it is only usable once.

• An accumulator is the technical term for a rechargeable battery. It allows to store electricity and can be reused because its discharge process can be reversed.

• A battery is an accumulator, widely used to increase the voltage or extend the life of a device.
Several technologies are applied in electrochemical storage

3.2.2 Principle of Operation of Electrochemical Batteries

Electrochemical batteries store energy through reversible oxidation-reduction (redox) reactions occurring between two electrodes immersed in an electrolyte. During discharge, oxidation occurs at the anode and reduction occurs at the cathode, producing an electric current in the external circuit. During charging, the reverse electrochemical reaction takes place.

A typical electrochemical storage system consists of:

- ✓ An anode (negative electrode),
- ✓ A cathode (positive electrode),
- ✓ An electrolyte allowing ion transfer,
- ✓ A separator preventing short circuits.

General Electrochemical Reactions

During discharge:

At the anode (oxidation):

$$M \rightarrow M^{n+} + ne^{-}$$

At the cathode (reduction):

$$X^{n+} + ne^{-} \rightarrow X$$

Overall reaction:

$$M + X^{n+} \rightarrow M^{n+} + X$$

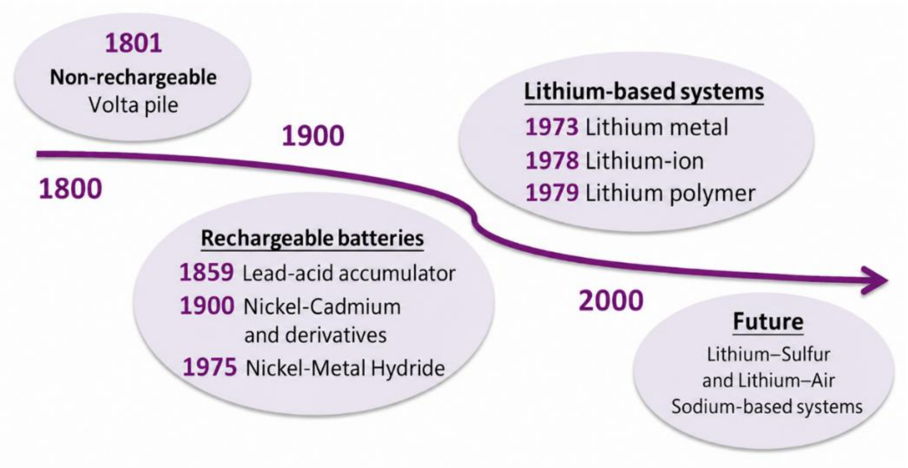


Figure 3-1 : Evolution of different battery systems (https://culturesciences.chimie.ens.fr/thematiques/chimie-physique/electrochimie/stockage-de-l-energie-evolution-des-batteries-12) accessed on 07/12/2025

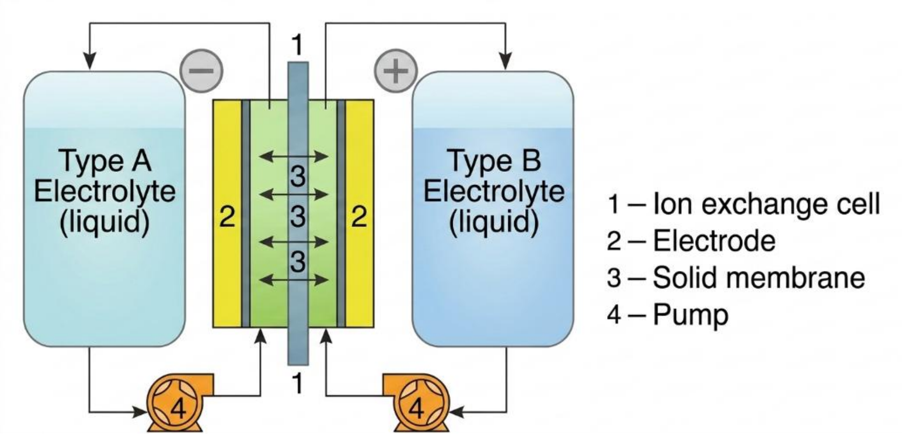


Figure 4. 6 : flow battery

From the invention of the first accumulators to the present day, the three chemistries on which different technologies are based are distinguished by their predominant use. Each of these technologies has distinct characteristics and meets specific needs:

3.2.2.1 Lead-acid batteries

Invented in 1859, the lead-acid battery is a set of lead-acid batteries connected in series in one housing. There are also gel batteries, lead batteries whose acid has been replaced by the gelatinized electrolyte. It is the most widely used battery type worldwide. Lead-acid batteries operate through electrochemical reactions between lead dioxide (PbO_2), sponge lead (Pb), and sulfuric acid (H_2SO_4).

$$Pb + PbO_2 + 2H_2SO_4 \rightleftarrows 2PbSO_4 + 2H_2O$$

Benefits:

• Lower cost compared to lithium-ion.

• Easy to implement, without the need for complex electronics such as a Battery Management System.

These batteries are mainly used for electricity storage and to power the electrical components of internal combustion engine vehicles, in particular the electric starter. When the engine is running, the battery is charged by a dynamo or alternator.

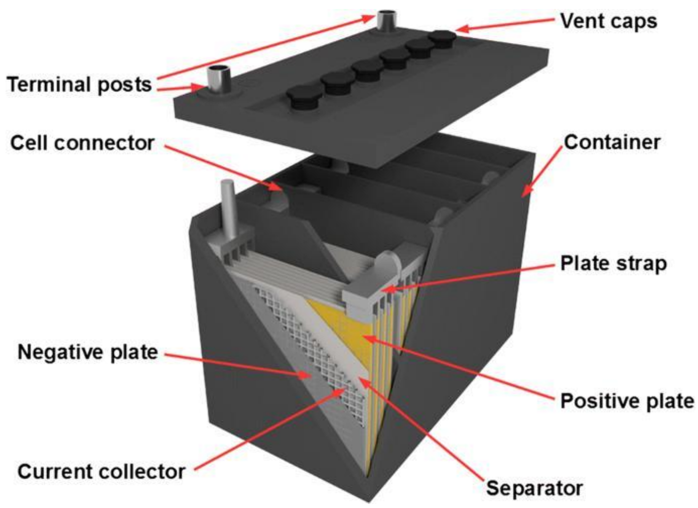


Figure 4. 7 Lead-acid batterie

Main Characteristics

- ✓ Low cost,
- ✓ High reliability,
- ✓ High recyclability,
- ✓ Heavy weight,
- ✓ Low energy density.

3.2.2.2 Nickel-Metal Hydride (NiMH) batteries

Nickel Metal Hydride (Ni-MH) batteries are assemblies of rechargeable electric batteries operating with metal hydride and nickel. They use a technology based on the chemistry of hydrogen and redox. Ni-MH batteries use hydrogen-absorbing metal alloys at the anode and nickel oxyhydroxide at the cathode.

Anode:

$$MH + OH^- \rightarrow M + H_2O + e^-$$

Cathode:

$$NiOOH + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-$$

Main Characteristics

- ✓ Moderate energy density,
- ✓ Good thermal stability,

- ✓ Environmentally safer than Ni-Cd batteries,
- ✓ Suitable for hybrid vehicles and solar applications.

Benefits:

- ✓ Higher energy capacity than lead-acid or NiCd (nickel-cadmium) batteries.
- ✓ Less polluting than lead-acid and lithium-ion batteries because they contain only limited toxic substances.
- ✓ Easy to store and transport as the conditions of transport do not require special regulations.

Today, these batteries are mainly used as solar batteries for outdoor applications such as solar lighting, monitoring, etc., due to their resistance to extreme temperatures and high safety level.

3.2.2.3 Lithium-ion batteries

Lithium-ion (Li-ion) batteries have evolved considerably in recent years and have become the most used for electrifying various applications, especially in the field of electromobility. Their operation is based on the transfer of lithium ions from the anode to the cathode during discharge, and vice versa during charging.

Lithium

-ion battery technology includes several types of chemistry that differ in their characteristics. For example, Lithium Nickel-Manganese-Cobalt (NMC) is compact and lightweight, providing high power for embedded solutions. Lithium Titanate (LTO) has a longer life than most other types of lithium (between 5,000 and 10,000 cycles or more).

Lithium-ion batteries operate through the movement of lithium ions between the graphite anode and the metal oxide cathode.

At the anode:

$$LiC_6 \rightarrow C_6 + Li^+ + e^-$$

At the cathode:

$$Li_{1-x}CoO_2 + xLi^+ + xe^- \rightarrow LiCoO_2$$

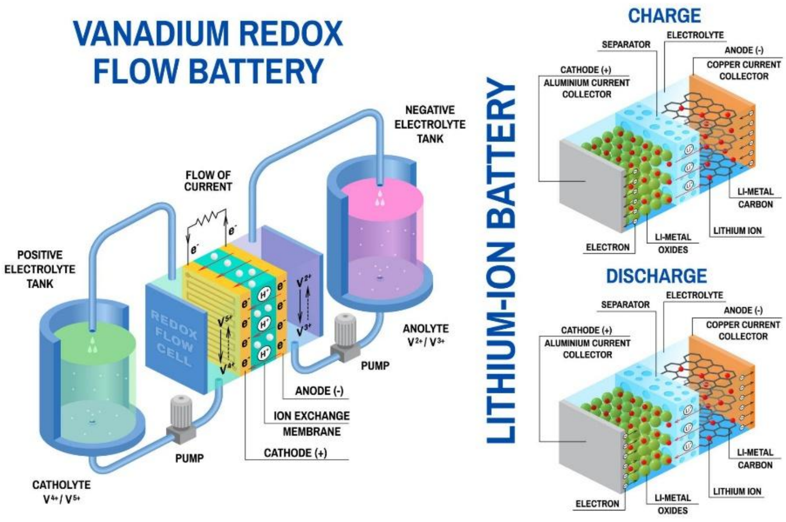


Figure 4. 8 Lithium-ion batteries

Main Characteristics

- ✓ High energy density,
- ✓ Low self-discharge,
- ✓ Long cycle life,
- ✓ Lightweight,
- ✓ Sensitive to overheating.

Benefits:

- ✓ Longer life than lead, Ni-Cd and Ni-MH batteries.
- ✓ High energy density for very low weight.
- ✓ No memory effect, meaning there is no voltage drop making the battery unusable when the voltage falls below the minimum threshold required for proper operation of the device.
- ✓ Low self-discharge (<5% per month).
- ✓ Lithium-ion batteries are suitable for several applications such as:
- ✓ Electric mobility for e-bikes.
- ✓ Agriculture for agricultural robots.
- ✓ Defence for surveillance drones.
- ✓ As well as for aeronautics, aerospace, defense, etc

3.2.2.4 New battery technologie

Let’s present two developments that could revolutionize the current market.

Sodium-ion (Na-ion) batteries

In competition with lithium-ion batteries in recent years, sodium-ion batteries technically work the same way as other batteries. The major difference is in the chemical composition of the cathode and anode, which incorporates sodium.

Discharge operation: An anode exchanges sodium (Na+) ions for electrons (e-) when the circuit discharges. The more positive ions (Na+) the battery contains to compensate for the negative charge of the electrons (e-), the longer it can provide energy.

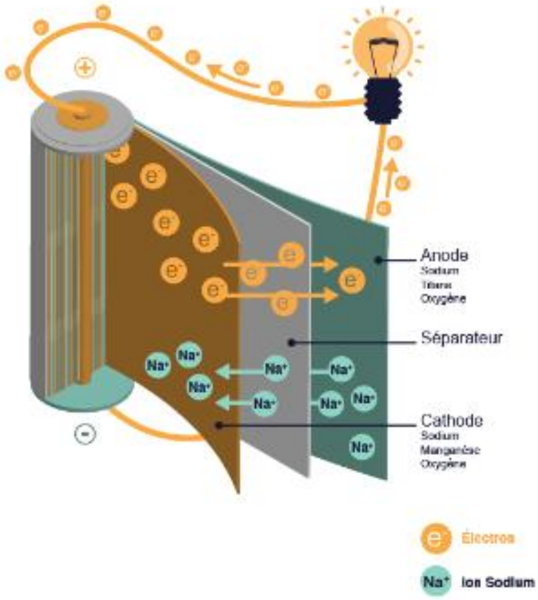


Figure 4. 9 : Sodium ion battery in discharge

Recharging operation: When you charge a Na-ion battery, the electrons (e-) circulate in the opposite direction and the sodium ions (Na+) return to their initial positions in the anode.

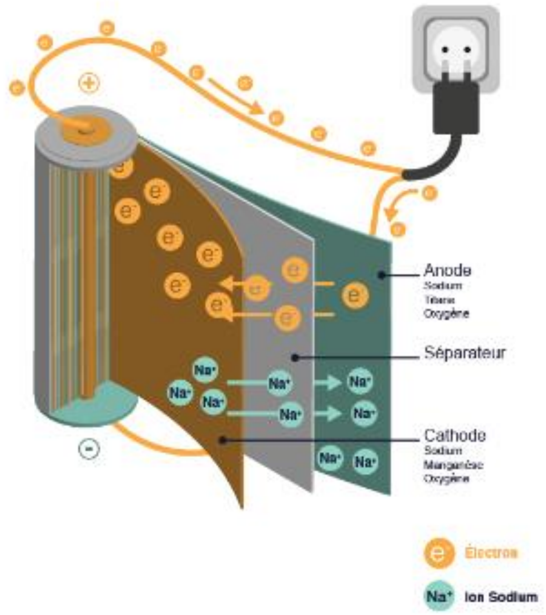


Figure 4. 10 : Sodium-ion battery in charge

Sodium-ion batteries are designed with an optimal number of charge-discharge cycles. Currently, the power of a Na-ion battery can reach 1 to 5 kW/kg in discharge, compared to 0.5 to 1 kW/kg for lithium-ion batteries.

Benefits:

- Although sodium-ion batteries do not yet offer a higher energy density than lithium-ion batteries, especially for electric vehicles, their use could fill several gaps in lithium-ion batteries:
- Raw materials rareness: Sodium is about 300 times more abundant on Earth than lithium, making 30 to 50% cheaper sodium-ion batteries than lithium-ion batteries.
- Safety: Sodium-ion batteries tend to heat up less than lithium-ion batteries, which reduces the risk of thermal runawaye.

3.2.3 Electrostatic storage :

Electrostatic storage stores energy in the form of electrons in a static electric field, without involving chemical reactions. This process occurs in devices such as capacitors and supercapacitors, which store electrical charges on conductive surfaces separated by an insulating (dielectric) material.

Supercapacitors, in particular, have a higher energy storage capacity than conventional capacitors and can be recharged and discharged quickly.

Electrostatic storage is often used in applications requiring fast response and fast charge and discharge cycles, such as regenerative braking systems in electric vehicles and high-power energy storage applications.

Operating Principle of Capacitors

A capacitor consists of two conductive plates separated by a dielectric material. Electrical energy is stored through charge accumulation on the plates.
The stored energy is expressed by:

$$E = \frac{1}{2}CV^2$$

where:

- ✓ E is the stored energy,
- ✓ C is the capacitance,
- ✓ V is the voltage.

Supercapacitors

Supercapacitors, also called ultracapacitors, have much higher capacitance than conventional capacitors. They combine:

- ✓ Very fast charging/discharging,
- ✓ High power density,
- ✓ Long cycle life,
- ✓ Excellent reliability.

However, their energy density remains lower than batteries.

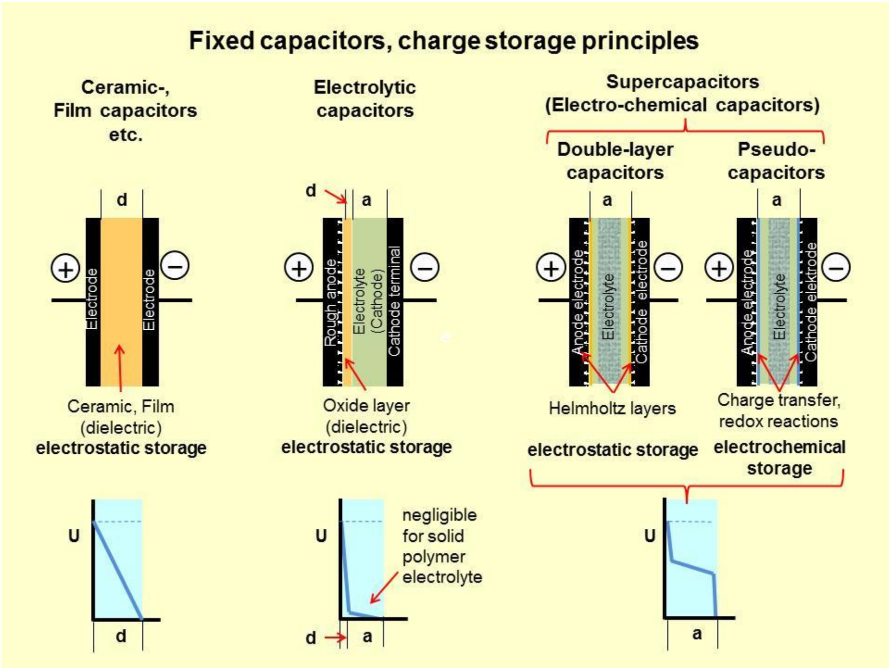


Figure 4. 11 Fixed capacitors

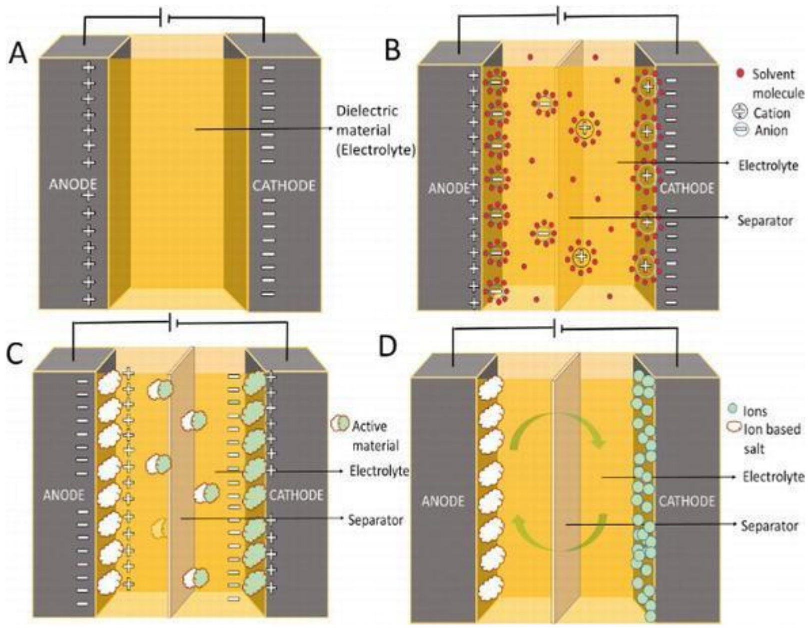


Figure 4. 12 Supercapacitor

3.3 Chemical storage: hydrogen and methane

3.3.1 Storage of hydrogen

HYDROGEN is considered the essential energy for the energy transition.

Among the promising energy storage vectors, hydrogen and methane attract particular attention because of their ability to store large amounts of energy in a dense and transportable form. This course will explore the principles and technologies of chemical storage for hydrogen and methane, addressing their advantages, disadvantages and potential applications.

Hydrogen is a single molecule composed of two hydrogen (H2) atoms. It has the highest energy density per unit mass of all fuels, making it an attractive choice for energy storage. However, its low density at room temperature poses a storage challenge.

3.3.1.1 Production of hydrogen

Hydrogen is not a primary energy source, such as oil or coal, but rather an energy carrier. This means that it must be produced from an energy source, just like electricity.

Dihydrogen (H2) is found in various terrestrial molecules, mainly in water (H2O), as well as hydrocarbons such as methane (CH4). To produce hydrogen, it is necessary to separate the dihydrogen from the other atoms constituting the molecule, that is to say oxygen in water and carbon in methane.

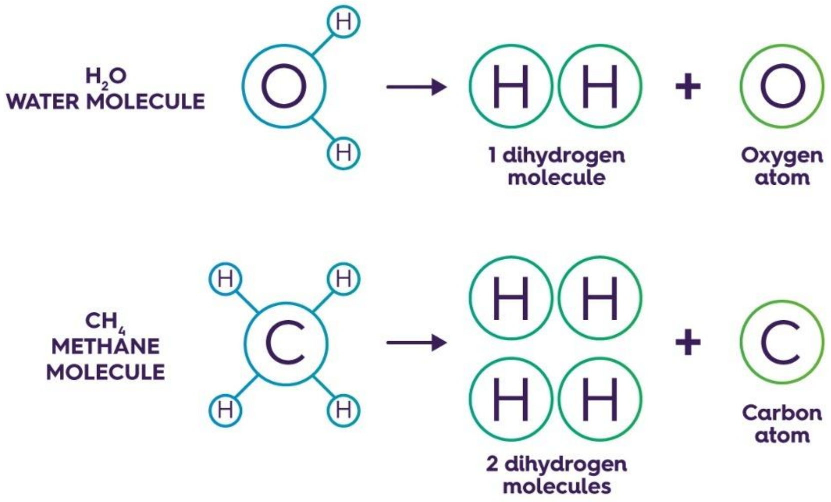


Figure 4. 13 : Composition of water and methane

There are several methods for producing hydrogen, each with its own specific advantages, disadvantages and applications.

Water electrolysis: In this process, water is separated into hydrogen and oxygen by an electric current. There are two main types of electrolysis: alkaline electrolysis, which uses an alkaline solution as the electrolyte, and proton-exchange membrane (PEM) electrolysis, which uses a proton-conducting polymer membrane. Water electrolysis is a clean method if it is powered by renewable electricity.

Reforming natural gas: Methane in natural gas can be converted to hydrogen by a reforming process, which can be achieved either by steam reforming or by partial oxidation reforming. This method is widely used commercially because of its cost-effectiveness, but it also generates CO2 emissions if the produced CO2 is not captured and stored.

Biomass gasification: Biomass, such as agricultural or forestry waste, can be converted into a gas mixture of hydrogen, carbon monoxide and carbon dioxide by a gasification process. The hydrogen can then be separated and purified for use.

Solar water electrolysis: This method uses solar energy to power the water electrolysis process, making it a fully renewable approach for hydrogen production.

Thermolysis: Thermolysis involves the thermal decomposition of water into hydrogen and oxygen at very high temperatures. This method is still under development and presents technological challenges, but has the potential to be a highly energy efficient hydrogen production method.

The color associated with hydrogen depends on its production method as a whole.

To date, more than 95% of the world's hydrogen production is based on fossil fuels, with greenhouse gas emissions. This hydrogen called "grey" is the most economical.

The capture of greenhouse gases allows to produce a hydrogen called «blue», more expensive.

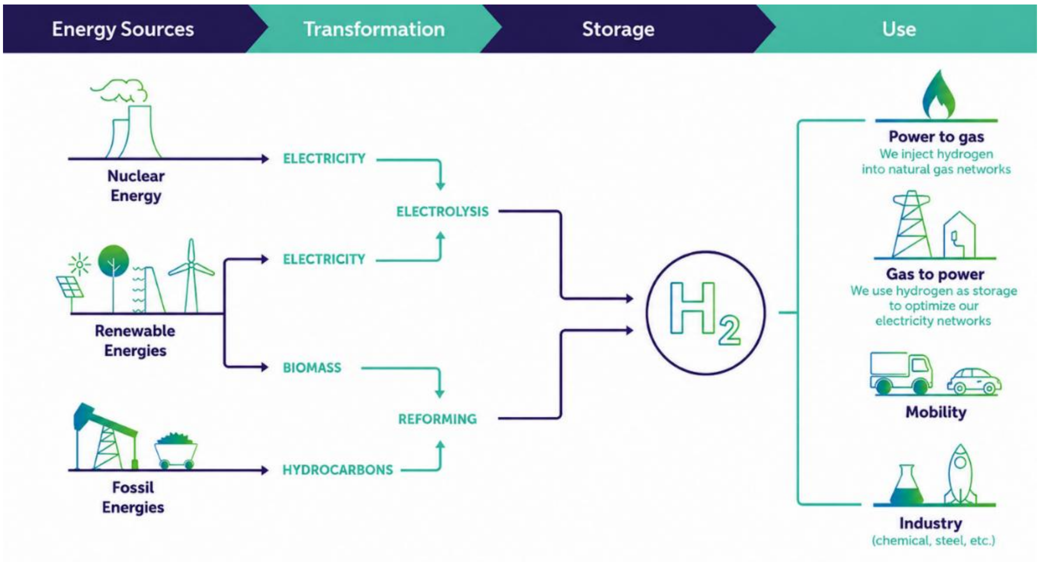


Figure 4. 14 : Production and use of hydrogen

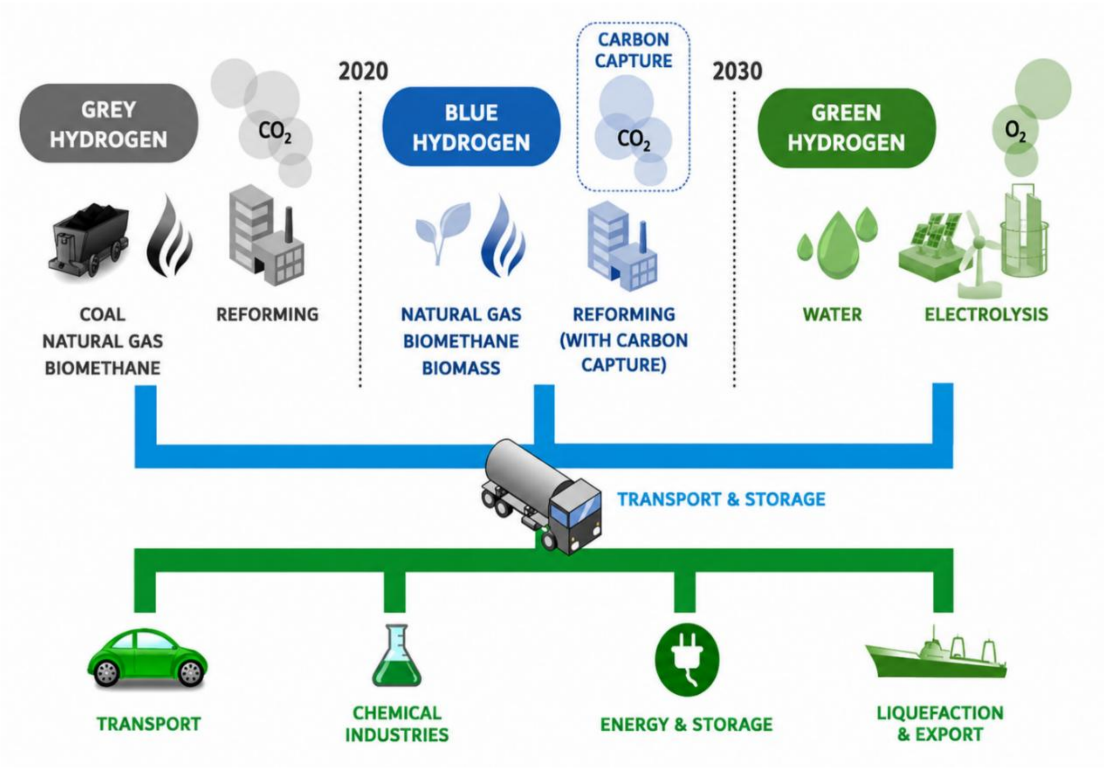


Figure 4. 15 Visualization of the 3 hydrogen production pathways (H2) and their name by a specific color. (https://www.chem4us.be/energie/h2/) accessed on 07/12/2025

If hydrogen is produced solely from solar energy, it is then attributed the green colour!

3.3.1.2 Hydrogen storage methods:

- **Gas storage:** Hydrogen can be stored in high pressure gas form in tanks. This method is simple and mature, but requires large pressure-resistant tanks.

Figure 3-2 : Hydrogen gas storage source (https://www.gexcon.com/resources/blog/hydrogen-fireball-in-a-storage-area-using-effects/) accessed on 17/12/2025

Cryogenic storage: Hydrogen can be liquefied by cooling at very low temperature (-253°C). This method allows to reduce the storage volume considerably, but it requires complex and energy-intensive cooling systems**.**

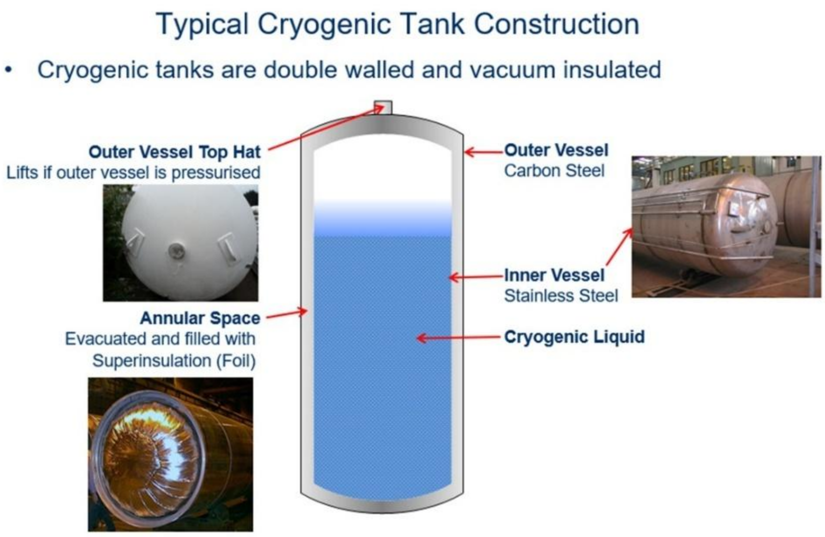


Figure 4. 16 : Hydrogen cryogenic storage. Source (https://h2tools.org/bestpractices/hydrogen-system-components/liquid-storage-vessels) accessed on 17/12/2025

- **Storage by metal hydrides**: Some metals, such as titanium or magnesium, can absorb and store hydrogen in their crystal structure. This method offers high storage density, but hydrogen release can be difficult and require specific conditions.

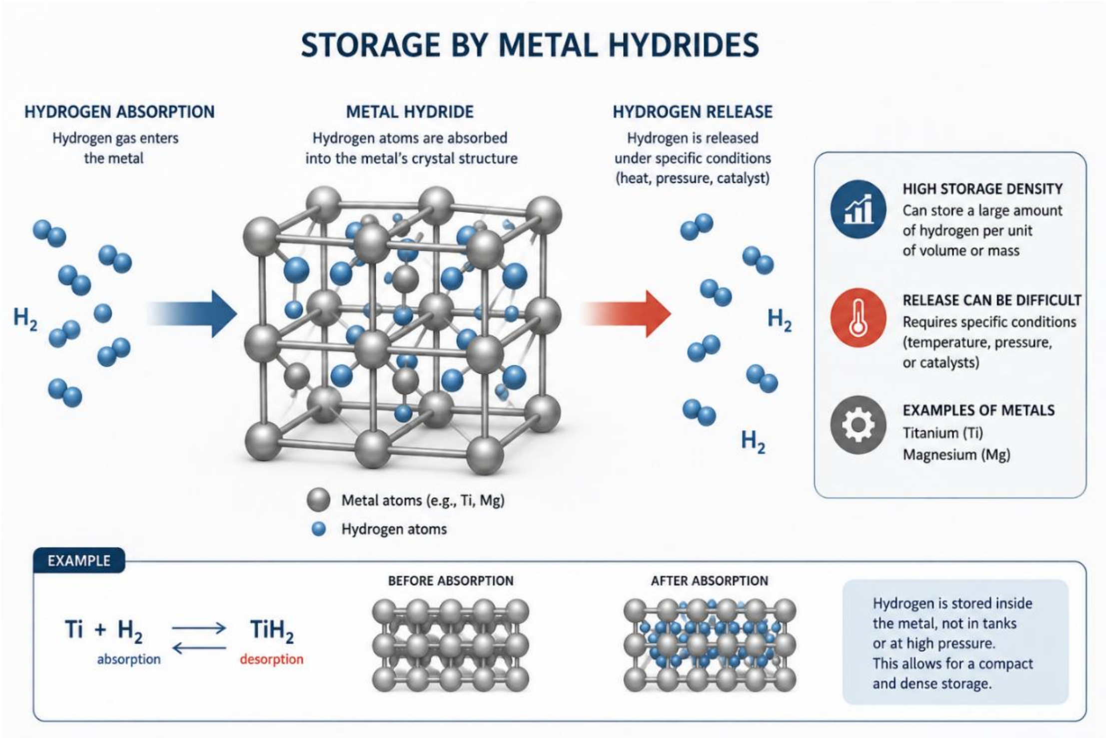


Figure 4. 17 : Hydrogen metal hydride storage (Laalam & Bazazi, 2025; Nemukula, Mtshali, & Nemangwele, 2025) Illustration generated using AI.

3.3.2 Methane storage

Methane (CH4) is the main component of natural gas. It is less energy dense than hydrogen, but has a higher density at room temperature, which makes it easier to store.

Methods of methane storage :

- **Gas storage:** Methane can be stored in high pressure gas form in tanks. This method is similar to hydrogen gas storage, but with lower pressure requirements.
- Liquefied natural gas (LNG) storage: Methane can be liquefied by cooling at -162°C. This method significantly reduces the volume of storage, but requires liquefaction and regasification facilities.

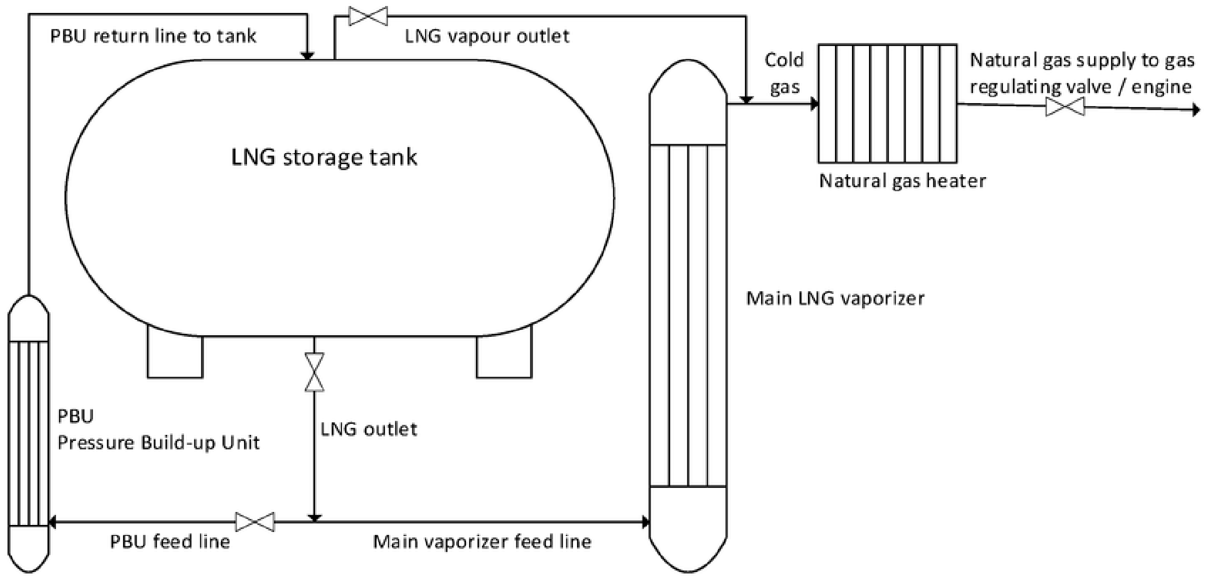


Figure 4. 18 : Liquefied natural gas (LNG) storage

- **Adsorption storage on activated carbon:** Methane can be adsorbed on porous surfaces of activated carbon. This method provides high storage density at room temperature, but the storage capacity is limited by the available surface area of the activated carbon.

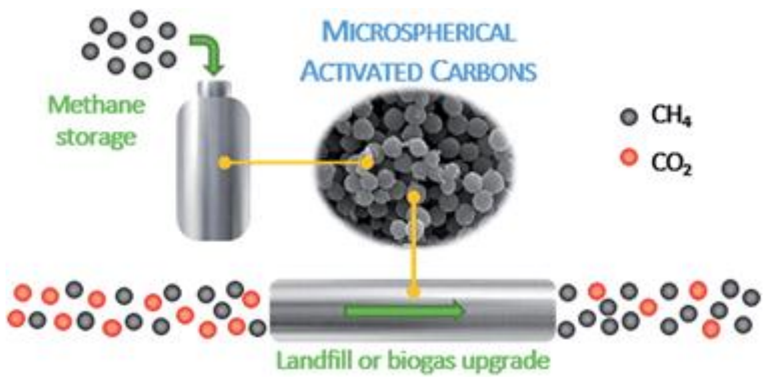


Figure 4. 19 : Activated carbon methane storage

3.3.3 Applications of hydrogen and methane storage

- ✓ Transportation: Hydrogen and methane can be used as fuels for fuel cell electric vehicles.

- ✓ Electricity generation: Hydrogen and methane can be used to generate electricity in combined cycle power plants.
- ✓ Balancing the electricity grid: Hydrogen and methane can be stored to store excess electricity from renewable energy sources and return it when demand peaks.
- ✓ Industry: Hydrogen can be used as a raw material in various industrial processes, such as ammonia production and methanol synthesis.

Chemical storage of hydrogen and methane offers significant potential for the development of sustainable, decarbonized energy systems. Storage technologies continue to evolve and improve, opening up new perspectives for the use of these energy carriers in a variety of applications.

3.4 Thermal energy storage technologies

Thermal Energy Storage (TES) is an innovative technology designed to capture and preserve thermal energy by heating or cooling a storage medium, enabling its later use in heating, cooling, and power generation applications. This versatile technology can store thermal energy in three primary forms: sensible heat within storage media, latent heat through phase change materials (PCMs), and thermo-chemical energy via chemical reactions. TES systems operate across an extensive temperature range from -40°C to over 400°C, with performance characteristics typically varying in terms of storage capacity, power output, efficiency, storage duration, and associated costs.

3.4.1 Sensible Heat Storage

Sensible heat storage is a well-established technology, widely used due to its simplicity and cost-effectiveness. By utilizing liquids or solids as a heat storage medium, this technology can store or release energy through temperature changes.

The core mechanism is expressed through the fundamental heat storage equation:

$$Q = m \cdot \boldsymbol{C_p} \cdot \Delta T$$

Where:

Q : Thermal energy quantity (Joules)
m : Mass of storage material (kilograms)

C_p: Specific heat capacity at constant pressure
ΔT: Temperature variation

Sensible heat storage systems employ solid (passive systems) or liquid media (passive or active systems such as molten salts, natural and synthetic oils, or water) to store thermal energy. The selection of a storage medium is influenced by various factors, including: cost-effectiveness, compatibility with the operating temperature and pressure requirements of the process, high thermal conductivity to minimize thermal inertia, high density and specific heat capacity to maximize energy storage density, compatibility with construction materials, and long-term stability and resistance to cycling.

3.4.2 Latent heat storage

Latent heat storage, employing Phase Change Materials (PCMs), offers an alternative to sensible heat storage [11]. PCMs can absorb or release significant amounts of energy, known as latent heat, during phase transitions between solid, liquid, and gas states. While liquid-gas phase changes exhibit the highest latent heat, their large volume changes make them impractical for storage. Solid-liquid PCMs, on the other hand, are commonly used and offer a substantial latent heat of transition.

To be effective, solid-liquid PCMs should have a melting point close to the desired operating temperature, melt congruently with minimal supercooling [22], and possess chemical stability, cost-effectiveness, non-toxicity, and non-corrosive properties.

The amount of energy stored in a latent heat storage system with PCMs can be calculated as:

$$E = \int_{T_i}^{T_m} m.C_{p,s}.dT + m.L + \int_{T_m}^{T_f} m.C_{p,l}.dT$$

Where:

E: stored heat (J)*m:* Mass of the PCM (kg)

$C_{p,s}$: Specific heat capacity of the PCM in solid phase (J/kg·K)

T: Melting temperature of the PCM (K)

T_i: Initial temperature of the PCM (K)

α: Fraction of the PCM that melts

L: Latent heat of fusion of the PCM (J/kg)

$C_{p,l}$: Specific heat capacity of the PCM in liquid phase (J/kg·K)

T_f: Final temperature of the PCM (K)

Latent heat thermal energy storage systems are typically considered passive storage solutions. Most implementations rely on solid-to-liquid phase transitions for energy storage. Compared to sensible heat storage, latent heat systems offer several advantages:

- **Smaller storage volumes:** Latent heat storage can pack more thermal energy into a smaller space.
- **Isothermal operation:** The temperature remains relatively constant during both charging (heating) and discharging (cooling) cycles.

However, there are also some challenges associated with latent heat storage:

- Complexity: Selecting and implementing the appropriate heat transfer technologies and choosing the optimal phase-change materials (PCMs) can be more intricate.
- Durability: Many PCMs exhibit a decrease in performance after repeated melting and solidification cycles.
- Heat transfer optimization: Optimizing heat transfer within the system can be complex.

3.4.2.1 Choosing the Right Phase-Change Material

Selecting a suitable PCM requires careful consideration of several factors:

- Phase-change temperature: This temperature should be appropriate for the intended application (heating or cooling).
- High latent heat of fusion: This value indicates the amount of energy absorbed or released during the phase change, directly impacting storage capacity.
- High density: A higher density PCM can store more thermal energy per unit volume.
- Minimal volume and pressure changes: Large volume and pressure variations during phase change can create design challenges.
- High thermal conductivity: Efficient heat transfer within the PCM is crucial for optimal performance.
- Long-term stability: The PCM should maintain its properties over extended periods at its operating temperature.

- Compatibility with building materials: For building applications, compatibility with surrounding materials is essential.
- Safety: The PCM should be non-toxic and non-flammable.
- Availability and cost**:** The material should be readily available and cost-effective.

Latent heat storage technology is mature for 0 °C, using ice and water. For other temperatures, it is still in its early stages of industrial development. Most research and development efforts have been conducted at the laboratory or prototype level.

3.4.2.2 Classification of Phase Change Materials (PCMs) for Thermal Energy Storage

3.4.2.2.1 Primary Categories

The diagram illustrates a comprehensive classification of PCMs, branching into two main transition types:

1. **Solid-Liquid** transitions
2. **Other Phase Transitions**:
    - Gas-Liquid
    - Gas-Solid
    - Solid-Solid

Material Composition Classes

Both main categories are further divided into two fundamental material types:

3.4.2.2.2 1. Organics

Split into two thermal behavior categories:

- **Eutectic single temperatures**: Materials with specific melting points
- **Mixtures temperature interval**: Materials with phase change over a temperature range

Organic Subcategories:

a) **Paraffins**:

- ✓ Alkanes mixtures
- ✓ Further classified into:

- Commercial grade
- Analytical grade

3.4.2.2.3 Inorganics

Categorized by their thermal behavior:

- **Mixtures single temperature**: Fixed melting point compounds
- **Mixtures temperature interval**: Variable phase change range
    - Notable example: Hydrated salts

3.4.2.2.4 Significance

This classification system provides a structured framework for:

- Understanding PCM types and properties
- Selecting appropriate materials for specific applications
- Organizing research and development efforts
- Identifying potential new PCM combinations

The hierarchical structure helps in systematic evaluation and selection of PCMs for various thermal energy storage applications.

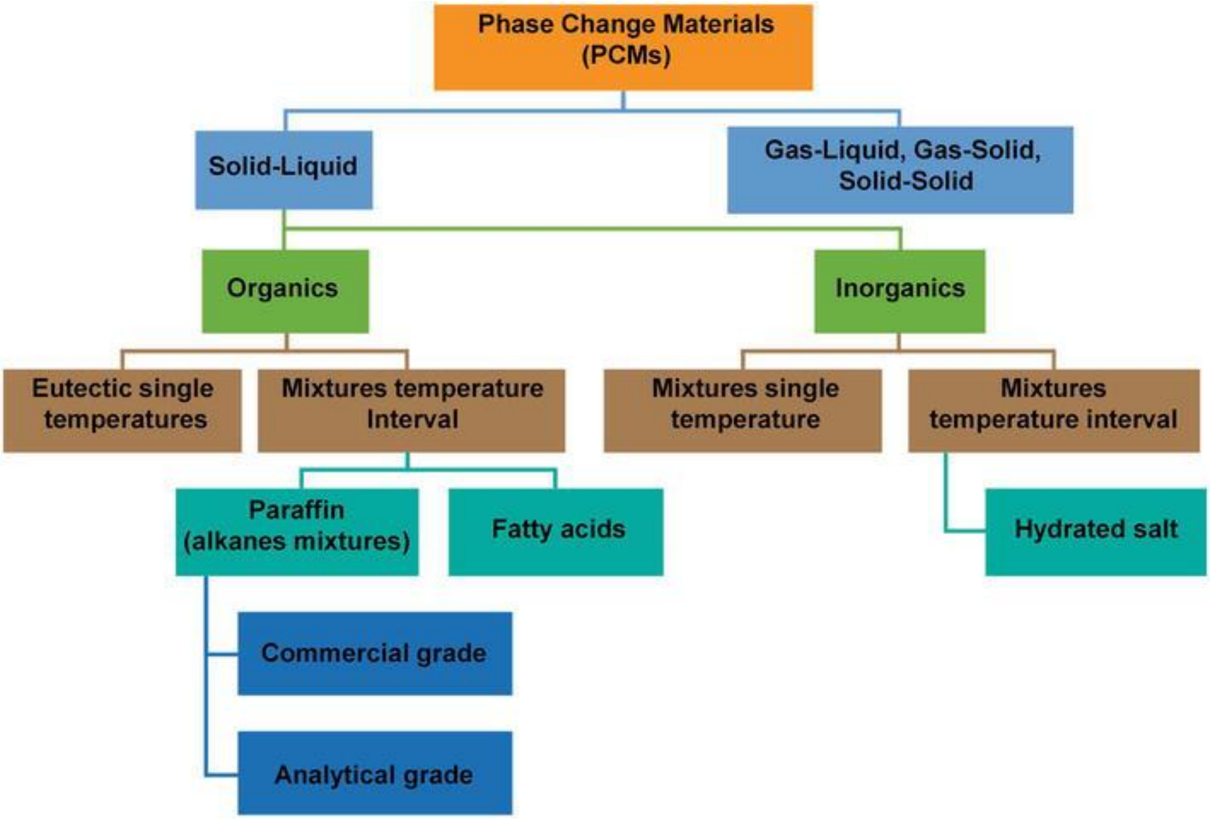


Figure 4. 20 : Classification of latent heat materials with solid–liquid phase change behavior. (Wang, Qin, Ji, & Tong, 2020)

3.4.3 Thermochemical energy storage

Thermochemical energy storage (TCES) is a technology that stores energy by harnessing reversible chemical reactions. In this process, heat energy is converted into chemical bonds. An endothermic reaction dissociates a reactant into its constituent products, which can be stored separately for extended periods. When energy is needed, the stored products recombine in an exothermic reaction, releasing heat.

TCES offers several advantages:

- High energy density: TCES materials can store significant amounts of energy per unit mass, ranging from 300 to 6,000 kJ/kg.
- Minimal heat loss: The chemical bonds in TCES materials can store energy for extended periods with minimal energy loss.
- Long-term storage potential: TCES enables long-term seasonal storage of thermal energy.

To be effective, TCES materials must possess the following characteristics:

- Large reaction enthalpy: A high energy release during the exothermic reaction.
- Fast reaction kinetics: Rapid reaction rates for efficient energy storage and release.
- High thermal conductivity: Efficient heat transfer within the material.
- Good cyclic stability: The material should maintain its performance over multiple cycles of charging and discharging.
- Abundant and economical elements: The materials should be readily available and affordable.

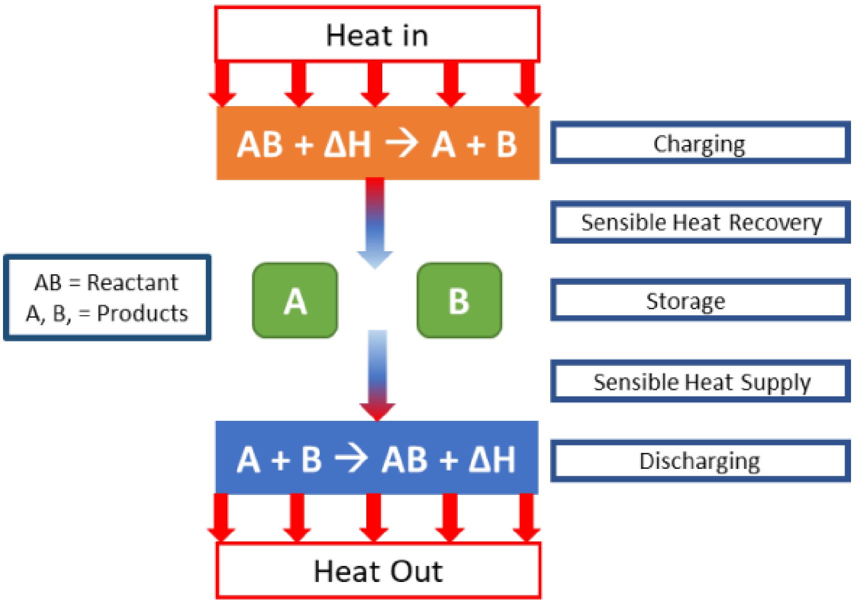


Figure 4. 21 : Thermochemical Energy Storage: Process: Charging, Storage, and Discharging

In general, reactions are of the form :

$$A + B + \Delta H_r \Leftrightarrow C + D$$

Typical reactions are of the form:

$$A + \Delta H_r \Leftrightarrow B + C$$

For thermochemical energy storage, the reaction must be entirely reversible to prevent the system from losing its storage capacity over cycles. **Erreur ! Source du renvoi introuvable.** presents a schematic of a basic thermochemical energy storage system.

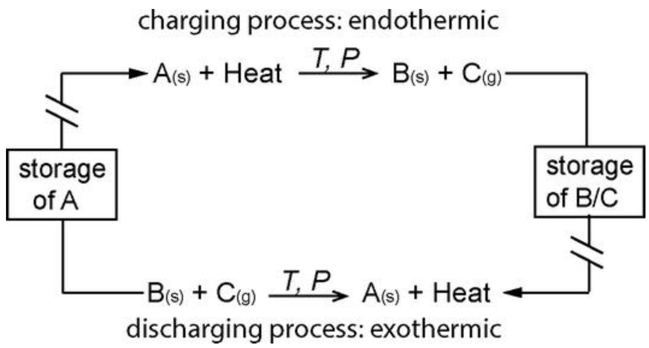


Figure 4. 22 : Thermochemical Storage System Schematic

During the charging phase, thermal energy from the solar field drives an endothermic reaction, producing substances B and C. These products are then separated and stored. When thermal energy needs to be recovered, the stored substances B and C are brought into contact, triggering an exothermic reaction. This reaction releases heat and regenerates the original substance A.

For example, magnesium hydride (MgH_2) and calcium hydride (CaH_2) have been investigated for thermal energy storage in concentrated solar power plants. Calcium hydride has been used to store heat at temperatures between 950°C and 1100°C. Magnesium hydride is the most extensively studied metal hydride for both hydrogen storage and thermal energy storage. The reaction involved is as follows:

$$MgH_{2(s)} + \Delta H_r \Leftrightarrow Mg_{(s)} + H_{2(g)}$$

The reaction enthalpy ΔH is 75 kJ/mol H_2, and operating temperatures range from 250°C to 500°C for hydrogen partial pressures between 0.1 and 10 MPa.

The amount of energy stored in a chemical reaction of type $A + \Delta H_r \Leftrightarrow B + C$ is the sum of the sensible energies of the materials and the heat of reaction. The energy stored can be expressed as follows:

$$E = \sum_{i=1}^{N} \int_{T_i}^{T_f} m_i.C_{p_i}.dT + n_A.\Delta H_r$$

Where E is the stored energy (J), n_A is the number of moles of product A (mol), and ΔH is the enthalpy of the reaction ($J.mol^{-1}{}_A$).

Equilibrium Temperature Equilibrium temperature is the temperature at which a reversible reaction can occur. It is a crucial parameter in selecting a suitable reaction, as it allows for a quick comparison based on the desired operating temperature. The equilibrium temperature, T_eq (K), can be approximated by the following equation:

$$T_{éq} = \left. \frac{\Delta H^0_{T_{réf}}}{\Delta S^0_{T_{réf}}} \right|_{\Delta C_p = 0 \ et \ K = 1}$$

Where ΔH° is the standard enthalpy of reaction (J/mol) and ΔS° is the standard entropy of reaction (J/mol·K). Two assumptions are made: there is no variation in specific heat $\left(\Delta C_p = 0\right)$, and the system is at equilibrium (K = 1).

Energy Density Energy density is a critical parameter in the development of energy storage systems. It represents the amount of energy stored per unit volume (kWh/m³) or mass (kWh/kg). This parameter significantly influences the size of the installation and, consequently, its cost.

The volumetric energy density, based on the volume of the reactant in the endothermic reaction "A," is defined as follows:

$$D_v = \frac{n_A . \Delta H_r}{V}$$

Where D_v is the volumetric energy density (J/m³), n_A is the number of moles reacting in the endothermic reaction (mol A), ΔH is the enthalpy of the reaction (J/mol A), and V is the volume of the storage material (m³).

Comparison of Storage Technologies Table 4. 1 compares the characteristics of the three thermal energy storage technologies discussed, and Figure 4. 23 summarises the energy storage technologies.

Table 4. 1 : Comparison of thermal energy storage and technologies

Technology	SHS	LHTES	TCS
Operating principle	Temperature change	Phase change	Reversible exothermic and endothermic reactions
Heat Storage density	~50 kWh/m^3 ~0.02–0.03 kWh/kg	~100 kWh/m^3 ~0.05–0.1 kWh/kg	~500 kWh/m^3 ~0.5–1 kWh/kg
Storage period	Limited (short-term)	Limited (short-term)	Long-term
Maturity	Commercialization	Mostly pilot systems	Laboratory-systems
Advantages	Simple operation; Low cost	High energy storage density; Stable temperature	Very high energy storage density; Flexible temperature ranges
Common Materials	Water, Oil, Molten salts, Metals, Rocks, Concrete, Ceramic	Ice, Salt hydrates, Paraffins	Metal halides, salt hydrates, salt solutions, zeolite, silica gel

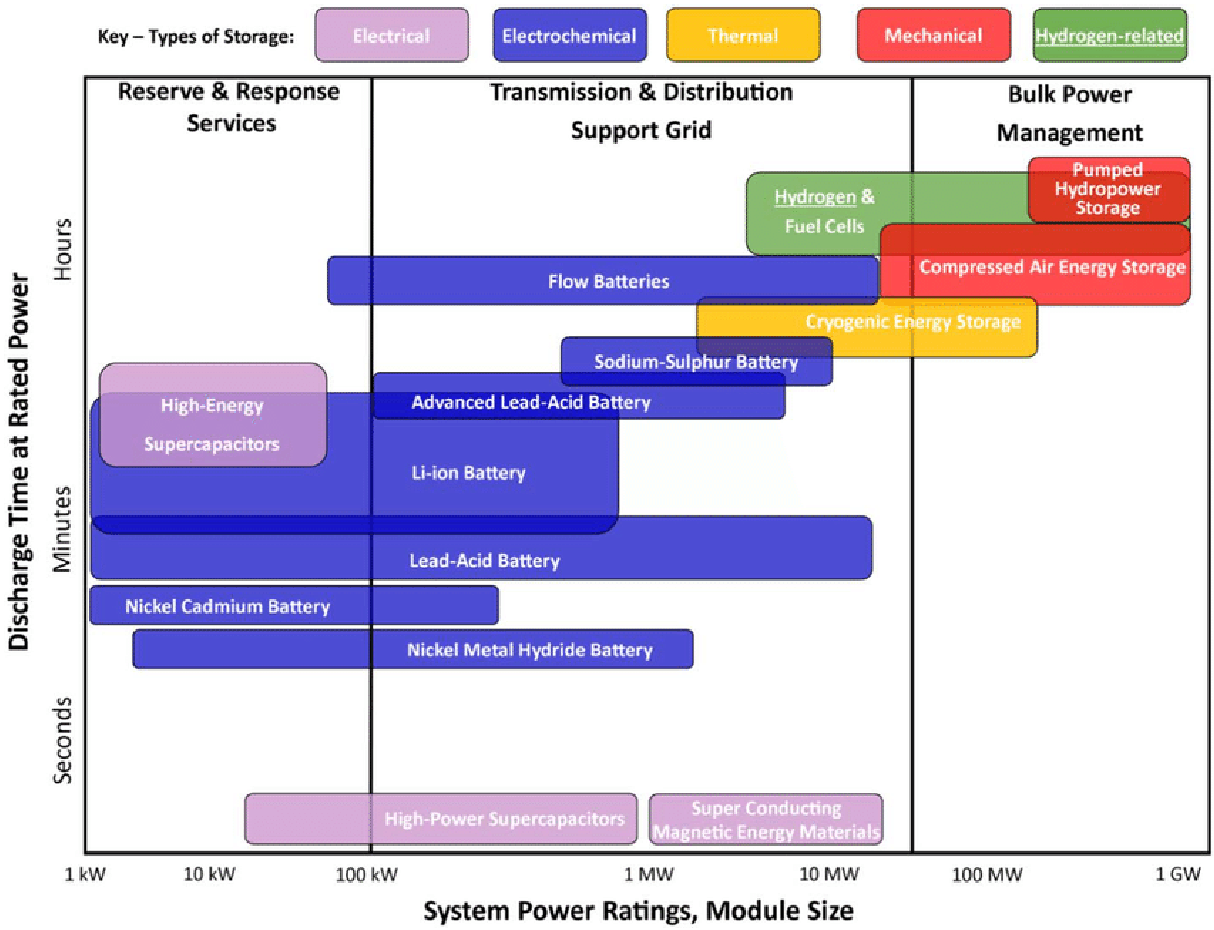


Figure 4. 23 : Energy Storage Technologies: Discharge Time and Capacity.

4 Energy Storage Cost

Energy storage cost is one of the most important factors in the development and deployment of modern energy systems. The economic viability of an energy storage technology depends not only on its initial investment cost, but also on its operating expenses, efficiency, lifespan, maintenance requirements, and environmental impact. Energy storage systems are essential for balancing energy supply and demand, improving grid stability, and integrating renewable energy sources such as solar and wind power.

4.1 Definition of Energy Storage Cost

The cost of energy storage refers to the total expenses associated with storing and delivering energy when needed. These costs generally include:

- ✓ Capital cost: the initial investment required for the storage system installation.
- ✓ Operation and maintenance cost (O&M): expenses related to system operation, monitoring, and maintenance.

- ✓ Energy conversion losses: losses occurring during charging and discharging processes.
- ✓ Replacement cost: costs associated with replacing components during the system lifetime.
- ✓ Environmental and recycling costs: costs related to waste management and environmental protection.

4.2 Factors Affecting Energy Storage Cost

Several parameters influence the overall cost of storage technologies:

4.2.1 Storage Capacity

Larger storage capacities generally require higher investment costs. However, economies of scale may reduce the cost per unit of stored energy.

4.2.2 Storage Technology

- ✓ Different technologies present different costs and performances:
- ✓ Batteries (Lithium-ion, Lead-acid)
- ✓ Pumped hydro storage
- ✓ Compressed air energy storage (CAES)
- ✓ Hydrogen storage
- ✓ Thermal energy storage

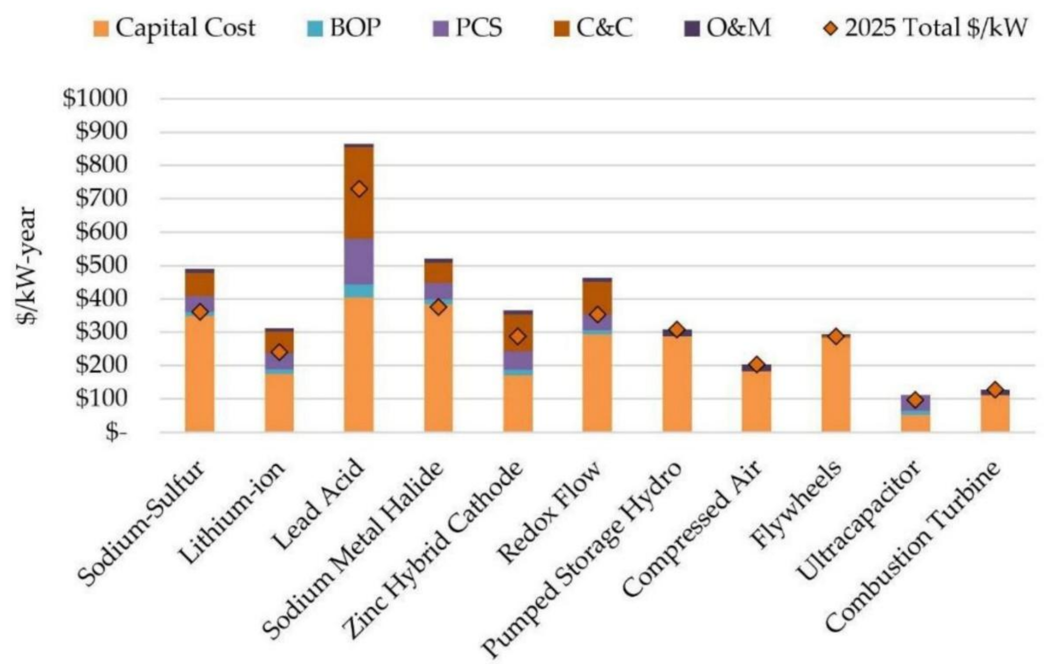


Figure 4. 24 Annualized costs for each technology by cost component. (Mongird et al., 2020)

4.2.2.1 Efficiency

High-efficiency systems reduce energy losses and improve economic performance.

4.2.2.2 Lifetime and Cycling Stability

Technologies with long operational lifetimes and high cycle durability are economically more attractive.

4.2.2.3 Safety and Environmental Constraints

Some storage systems require additional safety measures, which increase installation and operating costs.

4.3 Economic Indicators

The economic performance of energy storage systems is commonly evaluated using several indicators:

4.3.1 Levelized Cost of Storage (LCOS)

The LCOS represents the average cost of storing and delivering one unit of electricity over the system lifetime.

$$LCOST = \frac{\sum(Investment + Operation + Maintenance + Replacement)}{\sum Energy\ Delivered}$$

A lower LCOS indicates a more economically competitive storage technology.

4.3.2 Payback Period

The payback period corresponds to the time required to recover the initial investment through operational savings or revenues.

4.4 Comparison of Storage Technologies

Table 4. 2 indicates that energy storage technologies differ in terms of cost, efficiency, lifetime, and applications. Lithium-ion batteries provide high efficiency, whereas pumped hydro storage offers large storage capacity and long operational life. Hydrogen, thermal, and compressed air storage systems are mainly used for long-term and industrial energy storage applications.

Table 4. 2 Comparison of Storage Technologies

Storage Technology	Initial Cost	Efficiency	Lifetime	Typical Application
Lithium-ion Batteries	High	85–95%	10–15 years	Electric vehicles, grid storage
Pumped Hydro Storage	Very High	70–85%	>40 years	Large-scale grid storage
Hydrogen Storage	High	30–50%	Long	Seasonal energy storage
Thermal Storage	Medium	50–90%	Long	Heating and cooling
Compressed Air Storage	High	40–70%	Long	Industrial applications

5 Challenges and Future Perspectives

Despite technological progress, energy storage systems still face several economic challenges:

- ✓ High installation costs
- ✓ Material availability
- ✓ Recycling and environmental concerns
- ✓ Infrastructure requirements

Future research focuses on:

- ✓ Developing low-cost materials
- ✓ Improving storage efficiency
- ✓ Increasing system lifetime

- ✓ Reducing environmental impacts

Energy storage technologies are expected to play a key role in the transition toward sustainable and renewable energy systems.

6 Conclusion :

This chapter explored the different facets of energy storage, a crucial issue for the energy transition. The study of various forms of storage, ranging from traditional mechanical solutions to emerging technologies, demonstrates the richness and complexity of this field. The different technologies presented - whether mechanical, electrochemical, chemical or thermal - each offer specific advantages and meet distinct needs.

The analysis of energy efficiency and associated costs for each storage method highlights the importance of a balanced approach in choosing solutions, based on technical, economic and environmental constraints. New storage technologies, in constant development, offer promising prospects for meeting future energy challenges.

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