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Département d'Électronique

Polycopié Pédagogique

Autonomous Energy Systems

Cours destiné aux étudiants de :

Master 1 : Instrumentation.

Master 1 : Électronique des Systèmes Embarqués.

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PEDAGOGICAL SUMMARY

This manuscript gives a comprehensive overview of the principles, technologies, and difficulties involved in electric power generation. It focuses on the shift to renewable energy sources. It is divided into five chapters that build on each other:

- Fundamentals and energy mix: laws of thermodynamics, electromechanical machines, and a look at the different types of energy sources (fossil, nuclear, and renewables).
- Wind energy: from Betz's principle to industrial wind farms, including sizing and the Algerian case.
- Hybrid systems and tidal-stream energy: combining sources, storage, and presentation of tidal-stream energy.
- Solar photovoltaic energy: the photovoltaic effect, cell technologies, PV system components (modules, inverters, MPPT) and a case study.
- Overview of other RES: hydropower, biomass, geothermal, marine energies, and economic analysis using LCOE.

  Each chapter is meant to stand on its own, with clear learning goals, technical illustrations, comparison tables, and exercises for self-assessment. The approach is both theoretical and practical, and it uses examples from Algeria and international standards like IEC and IRENA.

  Target audience: undergraduate and graduate engineering students; engineers in continuing education; instructors; and anyone seeking a technical and system-level view of sustainable electricity generation.

  Learning objectives:

  - Master the physical principles of energy conversion.
  - Compare advantages, disadvantages, and costs of different sectors.
  - Size a simple system (wind turbine, photovoltaic).
  - Understand the challenges of integrating renewables into the power grid.

FOREWORD

- This document was designed as a course and reference material for teaching renewable energies and electricity generation systems.
- Its organization meets two requirements:
  - Clarity and progressive learning: fundamental concepts are introduced in Chapter 1 and then deepened in subsequent chapters through specific technologies.
  - Practical approach: each sector is illustrated with functional diagrams, up-to-date technical data (costs, efficiencies, power ratings), case studies, and exercises.
- How to use this handout:

- Lectures: follow the chapter progression; figures and tables are intended to be projected and discussed.
- Tutorials: use the self-assessment exercises, multiple-choice questions, and case studies provided at the end of each chapter.
- Personal projects: Chapters 2, 4, and 5 provide the basics needed to size a real installation.
- Revision: the “Key points” and “Review” sections at the end of each chapter provide a fast synthesis of the main ideas.

- Intended readers:
    - Bachelor's and Master's students in engineering sciences, instrumentation, and ESE...
    - Engineering students specializing in energy, electrical engineering, or mechanical engineering.
    - Professionals changing careers or in continuing education.
    - Teachers and trainers looking for a structured and illustrated resource

Recommended prerequisites: General knowledge.

Semestre:1
Unité d'enseignement: UED
Matière2: Systèmes énergétiques autonomes
VHS: 22h30 (Cours: 1h30)
Crédits: 1
Coefficient: 1

Objectifs de l'enseignement:

Susciter l'intérêt de l'étudiant aux énergies renouvelables en général et aux systèmes énergétiques exploitant l'énergie solaire ou éolienne en particulier. Faire acquérir à l'étudiant une certaine compétence dans le dimensionnement d'une installation éolienne ou photovoltaïque.

Connaissances préalables recommandées:

Connaissances générales

Contenu de la matière:

Chapitre 1 : Dispositifs de production d'énergie électrique,
Notions sur les transformations d'énergie (mécanique ; thermique ; hydraulique, …), Historique (Volta, Oersted, Faraday, etc.), l'alternateur, la dynamo, les modes de production de l'énergie électrique (centrale électrique hydraulique, les centrales thermiques). Les sources d'énergies non renouvelables (fossiles et nucléaires). Les sources d'énergies renouvelables.

Chapitre 2 : Energie éolienne
Historique, principe et structure, Caractéristiques et dimensionnement, Carte du gisement éolien en Algérie, Parcs éoliens et puissance, Normes, Avantages et inconvénients. Exemple d'une installation éolienne.

Chapitre 3 : Systèmes hybrides
Systèmes Hybrides (Hydrolienne, Principe de fonctionnement de l'hydrolienne, Les différents types d'hydroliennes et les exploitants,…)

Chapitre 4 : Energie solaire photovoltaïque
Principe d'une installation photovoltaïque, le gisement solaire en Algérie, Technologies des cellules photovoltaïques, Les modules photovoltaïques, MPPT, Caractéristiques et connectique photovoltaïque, Normes. L'onduleur (rôle, principe, caractéristiques et rendement). Exemple d'une installation photovoltaïque.

Chapitre 5 : Autres sources d'énergies renouvelables
Les familles d'énergie renouvelables (énergie solaire, énergie éolienne, énergie hydraulique, Biomasse, Géothermie). Les différentes énergies renouvelables dans le monde. Rentabilité.

Mode d'évaluation:

Examen: 100%.

Références bibliographiques :

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7. *http://www.cder.dz/spip.php?article1442*

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GENERAL INTRODUCTION

The 21st century is witnessing a profound and irreversible transformation of the global energy landscape. We have inherited a system centered on the intensive, centralized exploitation of fossil fuels, and now face a dual imperative: addressing the climate emergency, driven by unprecedented greenhouse gas accumulation, and ensuring energy security, jeopardized by volatile resource geopolitics and the finite nature of reserves. In this context, electricity—a noble and flexible energy vector—is more than ever the lifeblood of modern economies. Yet, its production lies at the heart of the crisis and must become the cornerstone of the solution.

This work explores the foundations, technologies, and strategies underpinning this transformation: the transition to a decarbonized, sustainable, and resilient electricity system. This is not a mere technological substitution but a complete paradigm shift, moving from a model based on combusting finite matter to one founded on capturing inexhaustible natural flows.

Our study starts with the fundamental principles of energy conversion. Chapter 1 establishes the fundamental physical and historical foundation, tracing the discoveries of Volta, Ørsted, and Faraday, which paved the way for mastering electricity. We analyze the primary machine of large-scale conversion—the alternator—and provide a critical overview of conventional production methods, from non-renewable sources (fossil and nuclear) to hydropower. This chapter introduces the different renewable sources. They will constitute tomorrow's energy mix. Our work delves into the core technological pillars of the transition. Chapter 2 is devoted to wind energy, detailing the evolution of the ancient windmill into a marvel of aerodynamics and electromechanical engineering capable of powering entire cities. Chapter 3 broadens the perspective by addressing the synergy of hybrid systems, which are crucial for overcoming the challenge of intermittency, and explores the promising potential and exceptional predictability of tidal energy. Chapter 4 focuses on the most disruptive technology of the last decade: solar photovoltaics. We dissect the physics of the photovoltaic cell, its plummeting costs, and its systemic integration, from module to grid.

Finally, Chapter 5 widens the scope to offer a comparative panorama of all other renewable sectors—including hydropower, biomass, geothermal, and marine energies—analyzing their economic viability through the lens of the Levelized Cost of Energy (LCOE).

The objectives of this manuscript are threefold:

To elucidate the physical principles and technological devices that convert primary energy into electricity.

To critically analyze the potential, advantages, disadvantages, and maturity of each renewable technology, with a particular focus on the Algerian context.

To synthesize the technical, economic, and systemic challenges of integrating variable and decentralized sources into a grid designed for a centralized model.

This manuscript goes beyond just reviewing the latest technologies and shows that creating a sustainable energy future depends less on technical or economic limits and more on political choices, social creativity, and industrial planning.It is this argument that we invite you to discover in the following pages.

CHAPTER 1: ELECTRICAL ENERGY GENERATION DEVICES

1.1 Introduction: The Centrality of Electrical Energy in the Modern World

Electrical energy is the basis of modern societies, powering everything from industry to digitalization. This chapter presents the theoretical, historical, and technological foundations of electricity generation. It reviews the thermodynamic principles governing electricity generation. It summarizes pillar historical milestones (Volta, Ørsted, Faraday). It compares alternators and dynamos. It surveys major generation sources and today's energy mix at the end.

1.2 Thermodynamic Principles and Foundations of Energy Conversion

Electricity generation is governed by the laws of thermodynamics, which constrain energy conversion and efficiency. The first law, or principle of energy conservation, is the foundation of all energy conversion [1]. Thus, in a generator, energy is not "created," but transformed from a primary form.

The second law, on the other hand, states that real transformations generate entropy and therefore unavoidable losses. It states that any real process is associated with an increase in entropy, implying unavoidable losses, mostly dissipated as heat.

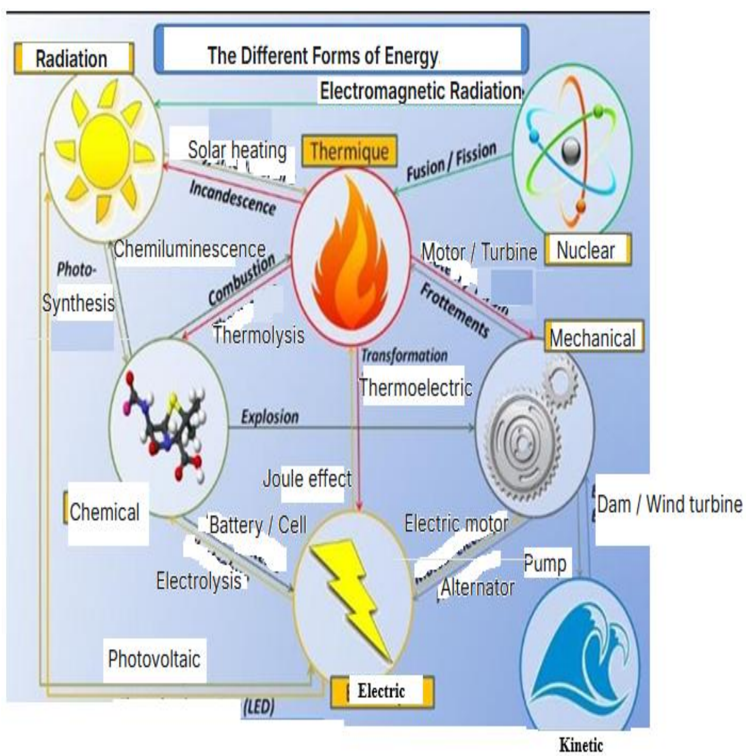

Fig. 1.1 : Diagram of the primary energy conversion chains (mechanical, thermal, radiant, and chemical) to electricity [1].

The conversion efficiency η is defined by:

$$\eta = \frac{\text{Useful energy output}}{\text{Primary energy input}} \times 100\% \tag{1.1}$$

These are the main conversion chains [1]:

Electromechanical Conversion: (Mechanical Energy → Electrical): This is where electromagnetic induction becomes important. An alternator converts the kinetic energy of a rotating mass, such as a turbine driven by water, steam, or wind, into electrical energy. It is the most widespread method for large-scale electricity production.

Advantage: High electromechanical conversion efficiency (often above 95% for a large alternator).

Limitation: The overall efficiency is that of the complete chain (e.g., boiler thermal efficiency + turbine efficiency + alternator efficiency).

1. **Thermo-Mechanical-Electrical Conversion (Thermal/Chemical/Nuclear Energy → Mechanical → Electrical)**: This is the most complicated chain, and it has the most losses. Combustion or fission creates heat, which is then used to make a working fluid (steam) at high temperature and pressure. When this fluid goes through a turbine, it changes thermal energy into mechanical energy, and then into electricity.

   Advantage: It allows the use of sources with very high energy density, such as coal and uranium.

   Limitation: Theoretically, the efficiency of thermal machines is limited by Carnot efficiency

   $$\eta_{\text{Carnot}} = 1 - \frac{T_c}{T_h} \tag{1.2}$$

   where Th and Tc are the absolute temperatures (K) of the hot and cold reservoirs

   For old coal plants, the overall efficiency is typically around 33% [2].

2. **Photovoltaic Conversion (Radiant Energy → Electrical)**: This is a direct conversion from one form of energy to another without any moving parts. The photovoltaic effect in a semiconductor makes it happen. Photons from the sun excite electrons, which causes a difference in potential.

   Advantage: It can be converted without making noise and without releasing any emissions. Constraints: The conversion efficiency in commercial modules remains low (15-22%) and power output is intermittent [3].

3. **Electrochemical Conversion (Chemical Energy → Electrical)**: Batteries and accumulators can change chemical energy directly into electrical energy. A spontaneous redox reaction creates a direct current. Benefit: Production that is portable and reliable, which is important for electronics. Limitation: High cost and low energy density for large-scale storage that doesn't move.

1.3 History of Foundational Discoveries: From Scientific Curiosity to Industrial Revolution

The mastery of electricity is not a matter of chance; it is the outcome of a coherent progression of meticulous scientific discoveries over nearly a century [4].

1.3.1 The Beginning of Direct Current (1800) by Alessandro Volta

Before Volta, electricity was mainly a subject of scientific curiosity (friction, lightning). Its design - a pile of zinc and copper discs interleaved with felt, soaked in salt water - was a significant technological step forward. A continuous and regular flow of electricity could now be obtained for the first time [5]. This system constituted the first electrochemical cell and a direct chemical-to-electrical energy conversion process. This invention opened the way to work on electrolysis and electromagnetism.

1.3.2 Hans Christian Ørsted and the Basic Link (1820)

Ørsted's discovery filled a key missing link. During a demonstration before his students, he observed that the needle of a compass was deflected when an electrical current flowed through a nearby wire. This seemingly simple experiment established for the first time, irrefutably, the link between electricity and magnetism: an electrical current **generates a circular magnetic field** around its conductor [6]. It opened the way to the design of electromagnets and laid the theoretical foundation for Faraday's work.

1.3.3 Michael Faraday and the Discovery of Electromagnetic Induction (1831)

If Ørsted had demonstrated that electricity generates magnetism, Faraday pursued and identified the inverse relationship. He showed through a series of careful experiments that a changing magnetic field can make an electrical current flow through a closed conductive circuit [7]. This is the principle of electromagnetic induction. His devices, such as the coil in which he moved a magnet, are the direct prototypes of modern electrical generators. This discovery underpins modern electricity generation.

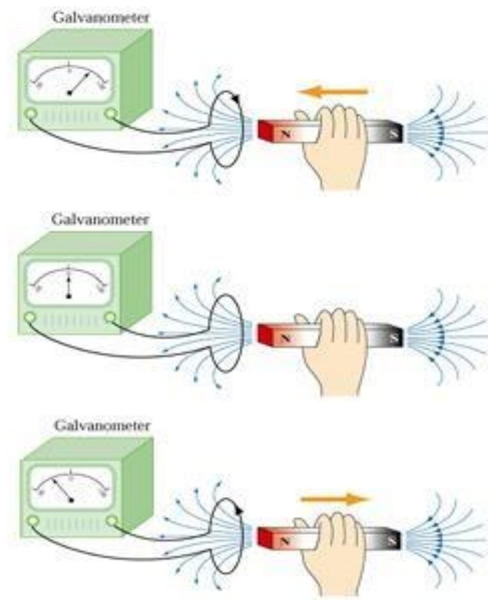

Fig. 1.2 : Schematic representation of Faraday's principle of electromagnetic induction: a magnet moved within a coil generates an electric current [7].

1.3.4 Subsequent Developments and the "War of the Currents"

These developments triggered major technological and industrial advances. Thomas Edison was a strong supporter of direct current (DC) for distributing electricity. George Westinghouse, on the other hand, used Nikola Tesla's work on alternating current (AC) to fight Edison in a fierce technological and business battle. Alternating current's technical advantages for long-distance transmission (like how easy it is to change voltage with transformers) eventually won out, setting the standard for modern electrical networks [8].

1.4 A Comparison of the Alternator and the dynamo

The alternator and the dynamo rely on the same physical principle of electromagnetic induction, but are designed for different purposes [9].

1.4.1 The Alternator

The alternator is what makes the global electrical network work. The alternator produces alternating current (AC). Its structure is defined by:

The Stator is a fixed part with a ferromagnetic ring that holds copper windings (armatures). Most large alternators have three windings that are 120° apart, which makes a three-phase system possible.

The Rotor: The part that spins is called the field winding. It is a strong electromagnet that gets its power from a system of slip rings and brushes that send direct current to it. Rotor rotation produces a time-varying magnetic field.

The electrical frequency f is related to the mechanical rotational speed N and the number of pole pairs

$$f = pN \tag{1.3}$$

with N expressed in revolutions per second. To maintain 50 Hz (60 Hz in North America), the speed of power plant alternators is therefore perfectly controlled [9].

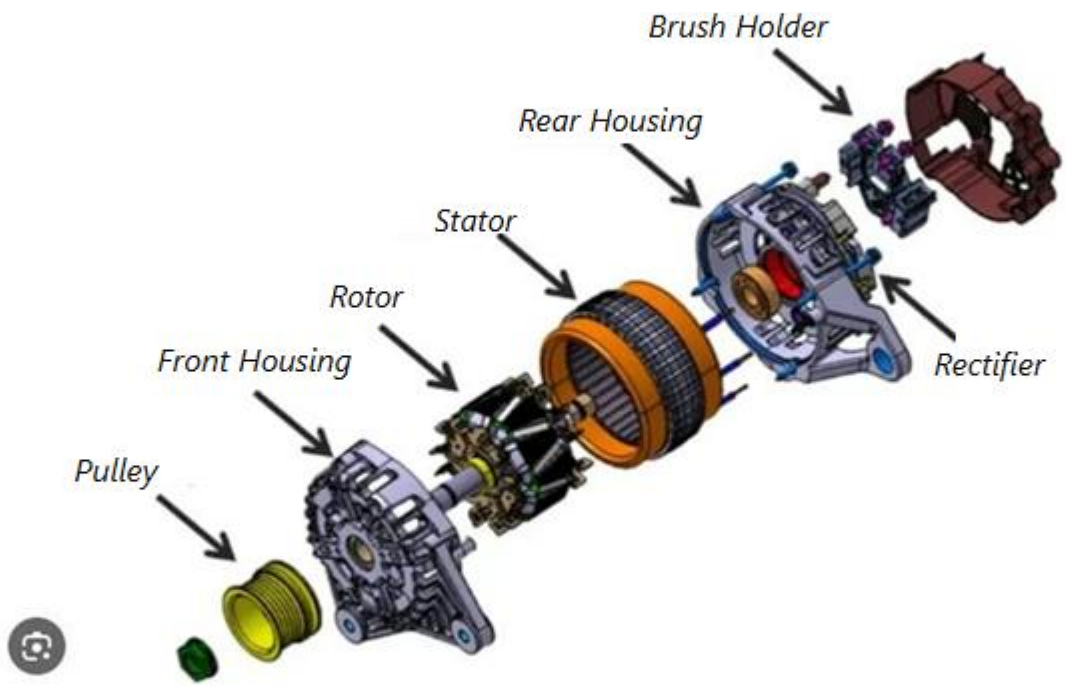

Fig. 1.3: Architecture of an alternator [8].

1.4.2 The Dynamo: The Direct Current Generator

The dynamo follows a different architecture to produce **direct current (DC)**:

- **The Armature (Rotor)**: It is the rotating part, consisting of a winding wound on a ferromagnetic core.
- **The Field Winding (Stator)**: A fixed part that makes a magnetic field that doesn't change (permanent magnets or electromagnets).
- **The Commutator and Brushes**: The commutator and brushes are the most important parts. The commutator is a segmented metal cylinder, insulated between segments, integral with the rotation shaft. It is in contact with fixed carbon brushes.

Operating Principle: The rotation of the armature in the fixed magnetic field induces an **alternating** EMF in it. The commutator's role is to mechanically switch the armature's connections with the external circuit so that the voltage at the brush terminals is always of the same polarity. The delivered current is not perfectly constant but "smoothed" by the presence of several coils on the armature and the system's inertia [9].

1.4.3 Technical Comparison and Areas of Application

Table 1.1: Technical Comparison of Alternators and Dynamos

Characteristic	Alternator	Dynamo
Type of current produced	Alternating Current (AC)	Direct Current (DC)
Rotating part	The magnetic field (Rotor)	The armature (Rotor)
Collection system	Smooth rings and brushes (low wear)	Segmented commutator and brushes (significant wear)
Efficiency & Power	Very high, up to several hundred MW	Lower, limited in power by commutator
Principal applications	Electric power plants of all sizes, generator sets	Formerly: vehicle lighting, battery charging. Today replaced by alternators + rectifier bridges

The table above shows the clear superiority of the alternator for mass production. The commutator–brush assembly cannot handle very high power, which is why it has been replaced by hybrid solutions. An alternator produces AC, which is then changed to DC using electronic diodes, which are much more reliable and efficient [9].

1.5 Electric Power Plants: Systemic Analysis of Production Modes

An electric power plant is a complex system that integrates a complete energy conversion chain. We analyze here the two principal archetypes.

1.5.1 The Hydroelectric Power Plant: Gravitational Energy Mastered

Hydroelectric power plants exploit renewable and low-emission water energy. Several types are distinguished [10]:

- **Run-of-river plants**: Without significant reservoir, they exploit the natural river flow. Production is relatively stable but remains non-dispatchable.
- **Lake plants (with dam)**: A dam creates a reservoir that stores potential energy. The hydraulic power is

$$P \approx \rho g Q H \tag{1.4}$$

where Q is the volumetric flow rate and H is the net head**.**

- **Pondage plants**: Intermediate, they have a limited reserve to generate during peak hours.
- **Pumped Energy Transfer Stations (STEP)**: These are "hydraulic batteries". They release water from an upper to a lower reservoir to generate electricity during peak demand hours. During off-peak hours, they use excess network electricity to pump water to the upper reservoir.

Conversion Chain:

Mechanical Energy → Electrical: The alternator is powered by the turbine.

1. **Potential Energy → Kinetic**: Water from the reservoir is sent through a penstock to the turbine below. Water pushes a turbine that is set up to work with the flow rate and drop height:
2. **Kinetic Energy → Mechanical**: Water drives a turbine adapted to the flow rate and drop height:
   - **Pelton turbine** (high drops, low flows)
   - **Francis turbine** (most common, medium drops and flows)
   - **Kaplan turbine** (low drops, high flows, and blades that can be changed)
3. **Mechanical Energy → Electrical**: The turbine drives the alternator.

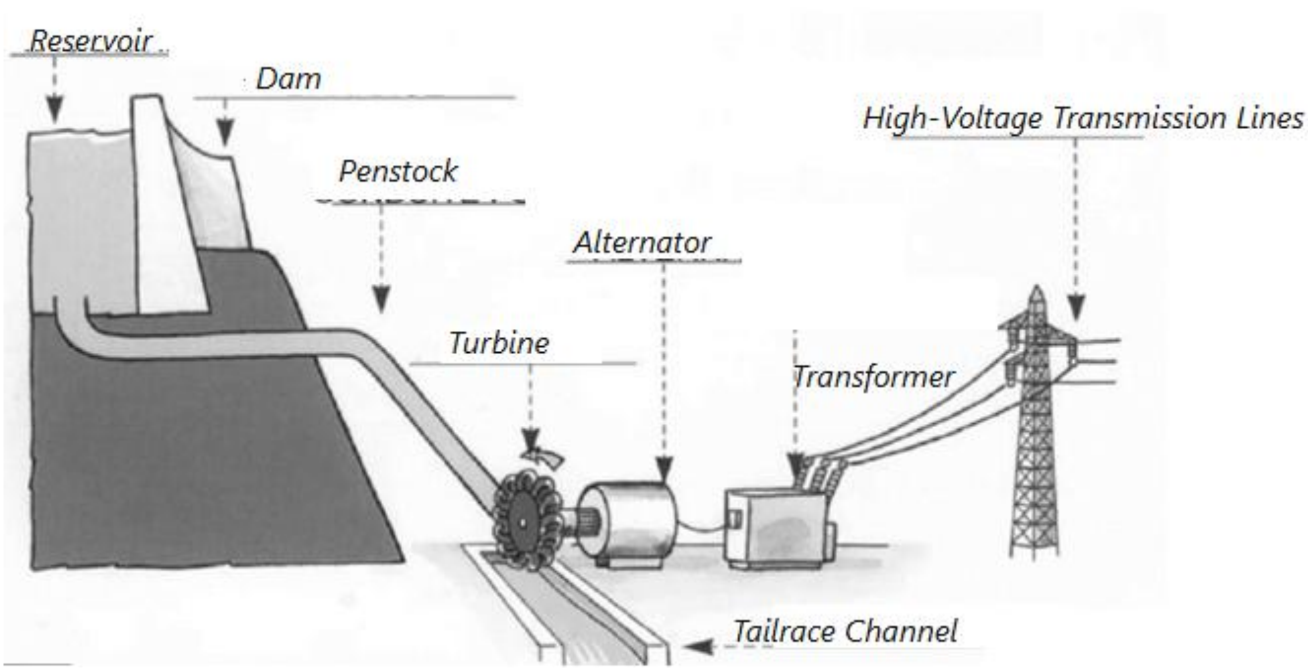

Fig. 1.4: Schematic diagram of a hydropower plant [9].

Advantages: Very high overall efficiency (≈90%), very fast startup (minutes), dispatchable production (except run-of-river), long lifespan, low operating costs [10].

Disadvantages: Significant environmental and social impact (valley flooding, ecosystem modification), colossal initial investment, precipitation dependence.

1.5.2 Thermal Power Plants: Conversion of Fossil Heat

These plants, while increasingly scrutinized, still account for a major share of global electricity generation and rely on the release of chemical energy through combustion [2].

Sub-types and Fuels:

- **Coal plants**: Historical technology. Coal is pulverized and burned in a boiler.
- **Oil plants**: They use heavy fuel oil.
- **Gas plants (gas turbine and combined cycle) use newer, more efficient technologies.**

A classic plant's conversion chain (steam only):

1. **Chemical → Thermal**: The fire in the boiler heats the water, which then turns into superheated, high-pressure steam (over 100 bar, 500°C).
2. **Thermal → Mechanical**: In a multi-stage steam turbine, steam expands. There are many blades on the walls of the turbine that direct the steam and send its energy to the shaft that is turning.
3. **Mechanical → Electrical**: The alternator is powered by the turbine shaft.
4. **Condensation and Regeneration**: A condenser, which gets its cold water from a river, sea, or cooling tower, turns steam from the turbine back into water. This step is very important for making a strong vacuum at the turbine outlet, which makes it work better. After that, the water goes back to the boiler, starting the cycle over again (Rankine Cycle).

The New Idea of Combined Cycle Gas-Steam Plants (CCGV):

CCGV plants are the most efficient. They put two cycles together [11]:

- **Brayton Cycle (Gas Turbine)**: Natural gas and compressed air are mixed and burned. In a gas turbine, combustion gases that are very hot (>1000°C) directly expand, driving a first alternator.
- **Rankine Cycle (Steam Turbine)**: Exhaust gases, still very hot (≈600°C), are sent to a heat recovery boiler (HRSG) to produce steam and drive a classic steam turbine, coupled to a second alternator.

Advantages of thermal plants: Production perfectly dispatchable and independent of weather conditions, lower investment cost than hydraulic (excluding CCGV), mature technology.

Major disadvantages:

- CO_2 emissions: A major contributor to climate change (especially coal). Pollutant emissions include SO_2, NO_x, and particulate matter.

- **Pollutant emissions**: SO_2 (acid rain), NOx, and fine particles are all pollutants that can harm health. It is required to have pollution control systems like desulfurization and denitrification, but they are expensive.

- **Efficiency**: Limited by thermodynamics. 30-40% for old coal plants to over 60-63% for best CCGV [2].

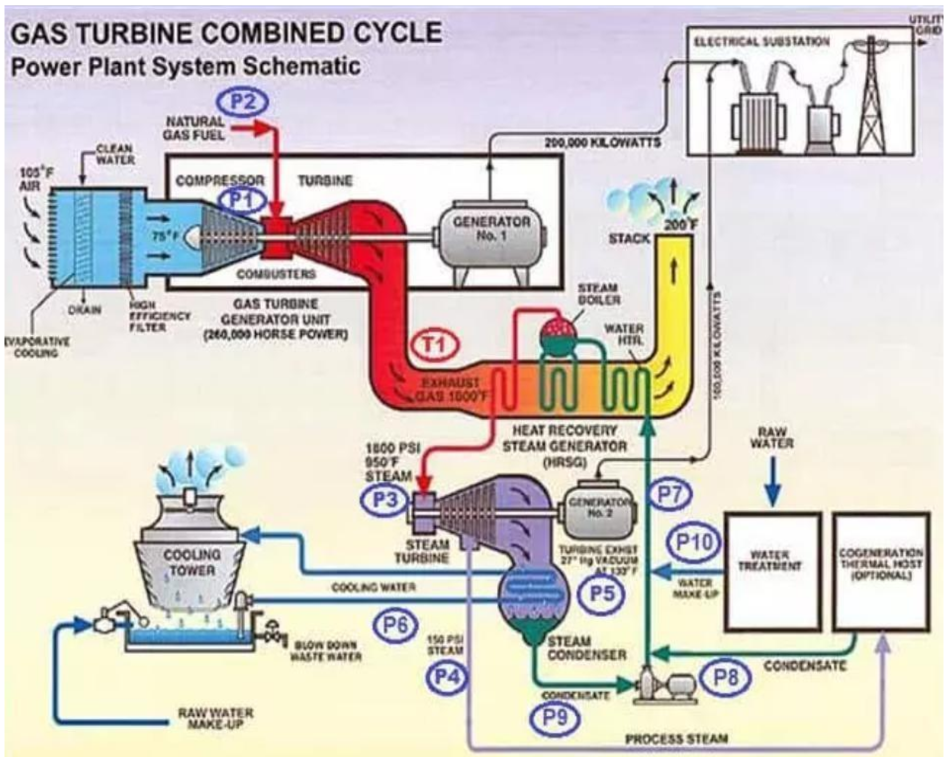

Fig. 1.5: Simplified diagram of a Combined Cycle Gas Turbine (CCGT) power plant, integrating a gas turbine and a steam turbine [10].

1.6 Non-Renewable Energy Sources: Critical Analysis

This category includes resources whose stock is limited on a human timescale.

1.6.1 Fossil Fuels: Heritage of the Carboniferous

Their formation required millions of years. Their rapid combustion imbalances the natural carbon cycle [2].

- **Coal**: The most abundant resource and geographically widespread. Its extraction (underground or open-pit mining) is dangerous and environmentally destructive. It is the fossil fuel with the highest CO_2 emissions per kWh produced.

- **Oil**: It is not often used to make electricity because it is so expensive. It is only used in some countries or for peak plants.

- **Natural Gas**: Natural gas is often considered the fossil fuel with the lowest specific emissions per kWh generated. When it burns, it releases about 50% less CO2 than coal for the same amount of energy. It emits fewer atmospheric pollutants.
- **Geopolitical problems**: The geographic concentration of reserves creates energy dependencies that can generate geopolitical tensions [2].

1.6.2 Nuclear Energy: Very High Energy Density

Civil nuclear energy uses the fission reaction of unstable heavy nuclei, like plutonium-239 or uranium-235 [12].

- **Principle**: When a neutron hits a fissile nucleus, it breaks into two lighter nuclei (fission products) and releases a huge amount of energy (according to $E=mc^2$) and a few neutrons that can keep the chain reaction going.
- **Reaction Control**: In a reactor, the chain reaction is controlled by control rods (boron or cadmium) that absorb excess neutrons.
- **Conversion Chain**: Heat released by fission is evacuated by a coolant fluid (water, sodium, gas) that transports this energy to a steam generator. The rest of the chain (steam → turbine → alternator) is identical to a classic thermal power plant.

Advantages:

- **Very low CO_2 emissions** during operation.
- **Massive, continuous and dispatchable production** (base operation).
- **Unmatched energy density**: 1 kg of uranium-235 gives off as much energy as burning about 2,700 tons of coal [12].

Problems and Difficulties:

Fission products are very radioactive and must be handled for a very long time (thousands of years). Deep geological disposal is a big problem for both society and technology. There is a risk of accidents: Modern reactors have a very low chance of having an accident, but the effects of a serious one (like Chernobyl or Fukushima) can be very bad. For nuclear proliferation, Civilian technology can be used for military purposes. Investments are enormous and construction timeframes very long.

1.7 Renewable Energy Sources: The Energy Basket of the Future

Renewable energies exploit continuous natural flows. Their development is at the heart of energy transition strategies [13].

1.7.1 Solar Energy:

Photovoltaic (PV): This is based on the photovoltaic effect in semiconductors, which are made of silicon. Cells are assembled into modules. Ground-based plants ("solar farms") are multiplying. Cost has fallen spectacularly, making PV competitive (LCOE - levelized cost of energy). The main challenge is **intermittence** (day/night, weather) and the need for storage solutions [3].

Concentrated Solar Power (CSP): Uses mirrors to concentrate radiation onto a receiver, heating a fluid. It makes energy from some thermal storage, like molten salts, after the sun goes down.

1.7.2 Wind Energy:

Principle: The wind's kinetic energy turns the blades of a propeller, which powers a speed multiplier (except for direct-drive models) [14].

Onshore wind: The most competitive. Challenges: a good social acceptability, impact on avifauna.

Offshore wind: Greater potential (stronger, more consistent winds) but higher investment and maintenance costs.

1.7.3 Bioenergy:

Uses organic matter (biomass): wood, agricultural residues, organic waste.

Electrical valorization: Direct combustion in power plants, or anaerobic digestion (breakdown producing biogas, mainly methane) which is then burned in a motor or turbine.

Considered carbon-neutral if resource is sustainably managed (emitted CO_2 was previously captured by plants) [15].

1.7.4 Geothermal:

Exploits Earth's internal heat. For electricity production, high-temperature resources are sought (>150°C), either in volcanic zones (natural steam sources) or through deep drilling.

Advantage: Continuous and dispatchable production, limited land footprint.

Challenge: Very geographically constrained location, high drilling costs, risk of reservoir decline [16].

1.7.5 Marine Energy:

Emerging field including tidal energy, current energy (hydrokinetic), wave energy and temperature gradient energy (OTEC).

Immense potential but technologies mostly at prototype stage, very high costs and aggressive marine environment [17].

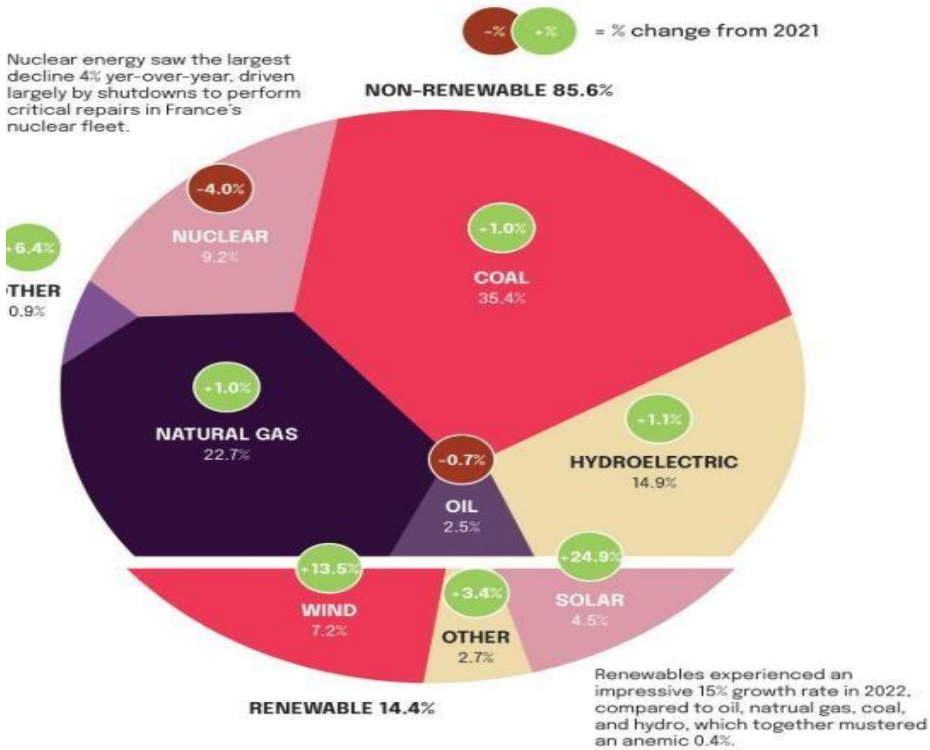

Fig. 1.6: Global distribution of electricity generation by source in 2022, illustrating the continued predominance of fossil fuels alongside the rapid growth of renewables [12].

1.8 Conclusion and Perspectives

This chapter has provided a thorough immersion into the world of electricity production. We have established that, despite the diversity of primary sources, conversion relies primarily on immutable physical principles: electromagnetic induction for final conversion and the laws of thermodynamics for thermal chains. The alternator emerged as the supreme machine for this large-scale conversion.

The current landscape is a complex and rapidly evolving mix. On one hand, non-renewable sources (fossil fuels and nuclear) provide most of the dispatchable and base production, but face colossal environmental and societal challenges. On the other hand, renewable energies are growing at an incredible rate because they are cheaper and better for the environment. However, integrating them into the grid is hard because they are not always available and the grid needs to be flexible.

The future of electricity generation will not depend on a single source, but rather on the creation of a diverse and optimized energy mix. This mix will intelligently combine nuclear power (for stable low-carbon base load), renewables [18-25] (to further decarbonize the mix), and possibly natural gas (for flexibility during the transition period).

Technological progress in energy storage (batteries, hydrogen), smart grids and energy efficiency will be the keystones for successfully achieving this transition to an electrical system that is both reliable, sustainable and accessible. Thus, conventional electricity production systems rely mainly on the thermo-mechanical conversion of primary energy, with efficiencies limited by the fundamental laws of thermodynamics and significant environmental impacts [20-23].

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KEY POINTS TO REMEMBER

Electricity production relies on transformation of primary energy (thermal, mechanical, radiant, chemical) **into electrical energy**, governed by:

First law of thermodynamics: energy conservation

Second law: entropy, efficiency limitation (Carnot)

1. **Modern electricity comes almost entirely from electromagnetic induction** (Faraday, 1831).
2. **Alternator = supreme machine** for AC production.

Very high efficiency

Slip ring system + field rotor

Frequency: The electrical frequency f is related to the mechanical speed N and the number of pole pairs p by $f = p \,.\, N$ with N expressed in revolutions per second.

3. **Dynamo** → obsolete due to mechanical commutator limitation → replaced by alternator + rectifier.

4. **Electric power plants = complete conversion chains**:

   Hydroelectric → excellent efficiency (≈90%)

   Thermal → limited by Carnot (33 to 63%)

   Nuclear → high energy density, low CO_2 emissions

   Renewable energies → rapid growth, intermittence

5. **Energy transition = optimized mix**: nuclear + renewables + flexible gas.

SELF-ASSESSMENT

QUESTION 1: Explain why the alternator dominates global electricity production.

SOLUTION:

The alternator dominates global electricity production for four major reasons:

1. **Very high efficiency** - Utility alternators achieve efficiencies exceeding 95%, thanks to electromagnetic induction and low wear of the slip ring-brush system.

2. **Three-phase AC production** - Three-phase power allows efficient long-distance transport and easy voltage transformation.

3. **Large available power** - Alternators reach several hundred MW.

4. **Absence of mechanical segmented commutator** - Unlike the dynamo, smooth slip rings significantly reduce wear.

Conclusion: robustness, power, durability and compatibility with modern networks explain the alternator's total dominance.

QUESTION 2: Detail how the second principle limits thermal power plant efficiency.

SOLUTION:

The second law of thermodynamics says that any real change must cause an increase in entropy. This means:

It is impossible to turn all heat into work.

Carnot cycle sets the highest level of efficiency.

Commonly low efficiencies:

Old coal plants: about 33%

Modern combined cycles: about 60%

Conclusion: The second principle stops any thermal machine from working at 100% efficiency, which is a hard limit for all thermal power plants.

QUESTION 3: What is the difference between a dynamo and an alternator?

SOLUTION:

Alternator (AC)

Makes three-phase AC power

Rotor = field winding (electromagnet)

Stator = armature (windings that don't move)

Smooth slip rings mean less wear.

Can handle a lot of power

Dynamo (DC)

Makes direct current

The rotor is the part that rotates.

Stator = field winding that doesn't move

Segmented commutator and brushes cause a lot of wear.

Limited power

Conclusion: The segmented commutator restricts dynamo power; it has been supplanted by an alternator and rectifier.

QUESTION 4: Tell the advantages about nuclear energy apart from the disadvantages.

SOLUTION :

Very little CO_2 released.

Production that is stable, huge, and easy to send out.

Very high energy density (1 kg of uranium-235 = about 2700 tons of coal)

Problems:

Radioactive waste that lasts a long time

There is a chance of big accidents (like Fukushima and Chernobyl)

Very high costs of investment

Long time to build

Risk of proliferation

Conclusion: Nuclear is still a strategic option, but it's complicated and expensive.

QUESTION 5: What is the conversion chain in a hydroelectric power plant?

SOLUTION :

This is how the hydroelectric plant works:

Potential Energy → Kinetic: Water falls from a reservoir through a penstock.

Kinetic Energy → Mechanical: A Pelton, Francis, or Kaplan turbine is powered by water.

Mechanical Energy → Electrical: The alternator is powered by the turbine.

Injection into the grid or transport

Conclusion: Hydroelectric plants are very efficient overall, with an efficiency of about 90%.

QUESTION 6: Why must flexible generation and storage resources be integrated into a grid with high renewable penetration?

SOLUTION:

Sources that come and go (solar: day/night; wind: changes with the wind)

Rapid changes → changes that could upset the balance of frequency and voltage

What it means to need adjustment:

Gas plants that can change

Storage (batteries, STEP)

Control that is smart

Grid historically designed for centralized, stable production, not thousands of variable sources.

Conclusion: Without flexibility, a grid with high renewable penetration becomes unstable.

MULTIPLE-CHOICE QUESTIONS

QUESTION 1: The alternator's frequency is related to rotation speed by:

A. $f = N^2$
B. $f = p \times N$
C. $f = N/p$
D. f = constant

SOLUTION: B

QUESTION 2: The Carnot efficiency limit for a thermal machine is determined by:

A. Temperatures of hot and cold sources
B. Fuel combustion rate
C. Turbine blade design
D. Alternator efficiency

SOLUTION: A

QUESTION 3: Which renewable energy source provides the most continuous, dispatchable production?

A. Solar photovoltaic
B. Wind energy
C. Geothermal
D. Tidal

SOLUTION: C

QUESTION 4: The amount of power a hydroelectric plant can make depends on:

A. Just the height of the drop

B. Just the speed of the water flow

C. Height of the drop and flow rate

D. Material for the turbine blades

SOLUTION: C

QUESTION 5: The "War of the Currents" led to:

A. The standard is now alternating current (AC).

B. Direct current (DC) becoming the norm

C. Both AC and DC are used the same amount

D. Neither one becoming the most important

SOLUTION: A

QUESTION 6: The best thing about nuclear energy is:

A. Low cost of building

B. Short time to build

C. Very low CO_2 emissions and high energy density

D. Completely solves waste disposal

SOLUTION: C

CHAPTER 2: WIND ENERGY

2.1 Introduction

Faced with energy and environmental limitations, renewable sources appear as a strategic alternative, among which wind energy occupies an increasing place in the global electricity mix. Wind energy has become an important part of the decarbonized electricity mix in the global context of the energy transition. It is a mature technology for large-scale electricity generation. In 2023, global installed wind capacity reached approximately 900 GW [1]. The purpose of this chapter is to give a full picture of the wind energy industry. We will look at how it has changed over time, explain the physical principles and technological architectures, and talk about sizing considerations. Particular attention is given to Algeria's wind potential, a critical analysis of its advantages and disadvantages, and the study of a typical installation, all while respecting current technical standards and norms.

2.2 History

Wind energy conversion is not a modern innovation. As early as the 7th century, the first simple windmills were built in Persia to grind grain and pump water [2]. In medieval Europe, this technology was improved and became an essential tool for farming and industry. Charles F. Brush, an American, is credited with inventing the electric wind turbine. In 1888, he built a 12 kW machine to power his home with direct current [3]. With a rotor that is 17 meters in diameter, this wind turbine marked a turning point by shifting from purely mechanical to electrical energy conversion. The Jacobs models in the United States are some of the most famous small standalone wind turbines. In the 20th century, these kinds of turbines made it possible to bring electricity to remote rural areas. The oil shocks of the 1970s made people interested in this energy source again. The 21st century has seen the industrial deployment of wind power reach an unprecedented scale. Unit powers have continuously increased, from tens of kW to over 15 MW for the most recent offshore models [4]. This period is also marked by the emergence of offshore wind, which exploits stronger and more consistent winds, and by drastic cost optimization, making wind energy one of the cheapest electricity sources in many regions.

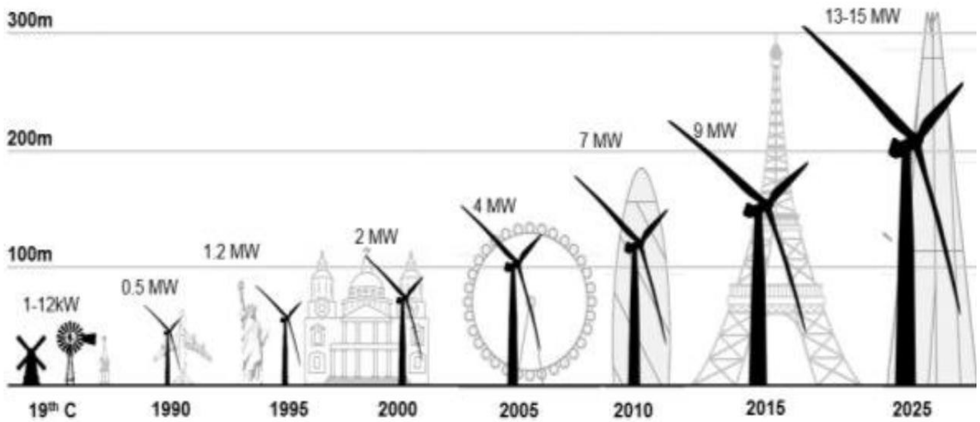

Fig. 2.1: Evolution of Wind Turbine Size and Power Capacity Over Time [4]

2.3 The Physical Principles and Structure of a Modern Wind Turbine

2.3.1 Basic Physical Laws

A basic law of physics says how much power can be recovered from wind. The kinetic energy in a moving mass of air is equal to its speed cubed. The theoretical power $P_{théorique}$ of a wind speed V passing through a surface S is given by:

$$P_{\text{theoretical}} = \frac{1}{2}\rho S V^3 \qquad (2.1)$$

where ρ is the air density.

However, it is physically impossible to capture all of this energy. In 1919, German engineer Albert Betz demonstrated that there exists a theoretical maximum efficiency limit for conversion, the power coefficient C_p, which cannot exceed $\frac{16}{27}$, or approximately **59.3%** [5]. This Betz limit applies to ideal axial-flow rotors in an unbounded flow, which is a good approximation for modern wind turbines [5]. The lift and drag of the air around the blade are what make it work, just like the wing of an airplane.

2.3.2 Architecture of a Horizontal Axis Wind Turbine

Horizontal axis wind turbines dominate the large power market. Their architecture is made up of several subsystems:

- **The Rotor**: There are usually three blades made of composite materials like fiberglass or carbon fiber, and a hub. It is the interface for capturing wind energy.
- **The Nacelle**: is the fairing that holds the main mechanical and electrical parts.
- **The System for Conversion:**

- A **mechanical gearbox** (except for direct-drive models) that speeds up the slow rotation of the rotor (usually 5–20 rpm) to the high speed needed by the generator (about 1000–1500 rpm).
- The **generator** (induction or, increasingly, synchronous with permanent magnets) that converts mechanical energy into electrical energy.

- **The Yaw System**: A servomotor rotates the nacelle to keep the rotor always facing the wind.
- **The Control and Safety System**: Includes mechanical brakes and a **blade pitch control system**, which modifies blade angle to regulate power and stop the machine in case of excessively strong winds.
- **The Tower**: Tubular steel or concrete structure supporting the nacelle and rotor. Its height is important for getting stronger and more laminar winds.

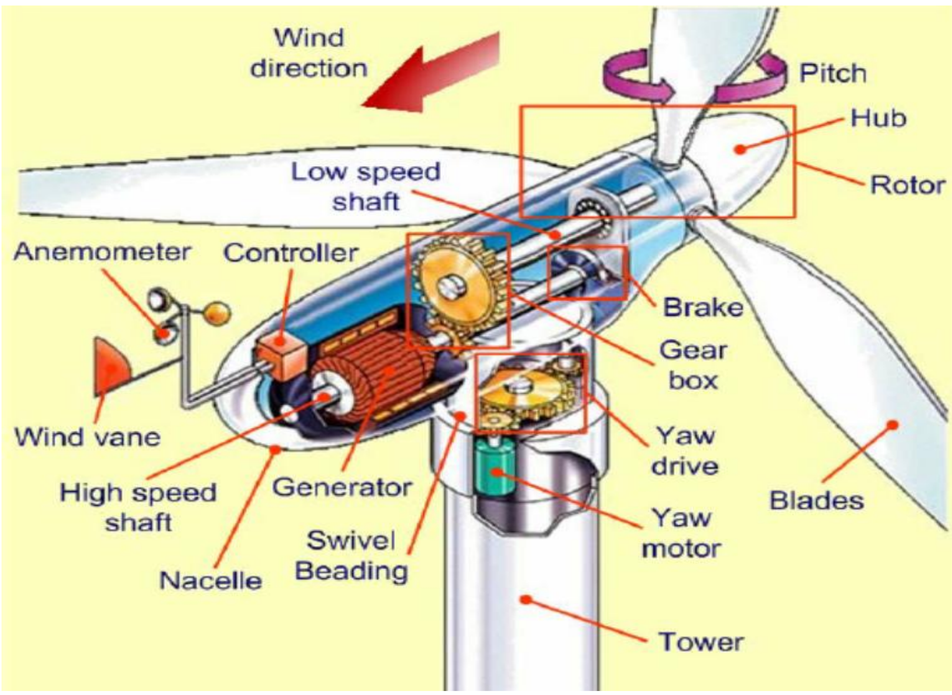

Fig. 2.2 - Cross-sectional diagram of a horizontal axis wind turbine with gearbox, showing the main internal nacelle components (rotor, gearbox, generator, yaw system) [6]

2.4 Technical Characteristics and Sizing

A wind turbine's performance is summarized by its **power curve**, which relates output electrical power to wind speed. The actual power $P_{réelle}$ is given by:

$$P_{\text{real}} = \frac{1}{2}\rho S V^3 C_p(\lambda)\eta \quad (2.2)$$

where $C_p(\lambda)$ is the power coefficient (dependent on the tip speed ratio λ), and η is the efficiency of mechanical and electrical components.

Analysis of this curve reveals three characteristic speeds:

- **Cut-in speed (3–4 m/s):** Below this, power is zero.
- **Rated speed** (12-15 m/s): Output power reaches its maximum (the machine's rated power).
- **Cut-out speed** (25 m/s): The wind turbine stops working to protect its structure.

Wind farm sizing requires an evaluation of the wind resource using anemometers and weather models. Optimization of machine layout is crucial to minimize **wake effects**, where an upstream turbine deprives downstream machines of part of the wind energy. An empirical rule consists of spacing turbines 5 to 9 rotor diameters in the prevailing wind direction [7].

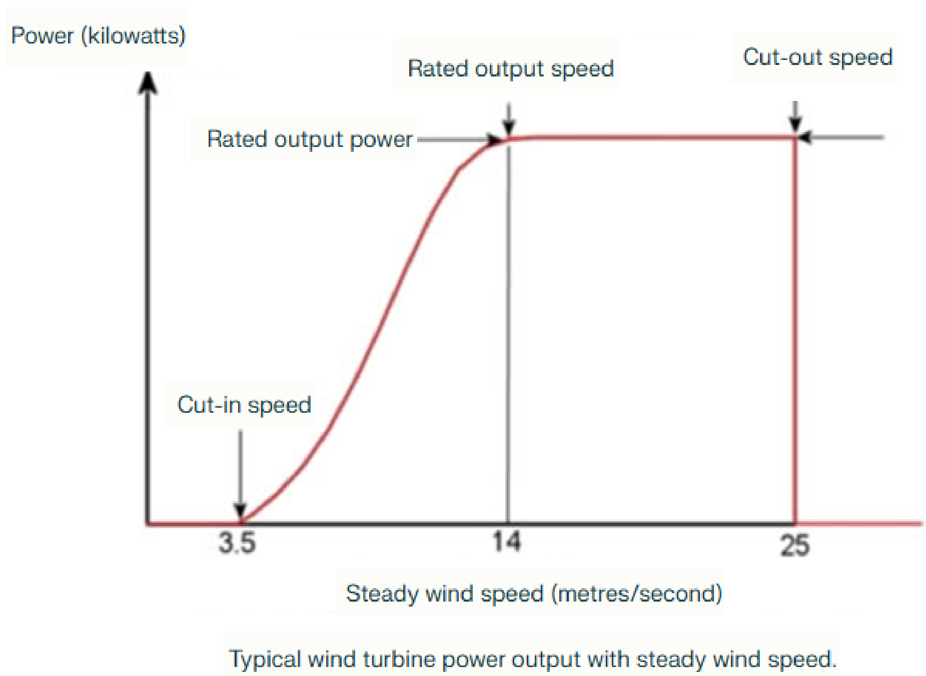

Fig. 2.3 - Typical power curve of a 2 MW wind turbine showing characteristic cut-in, rated, and cut-out speeds [14]

2.5 Algeria's wind resource map, wind farms and flagship projects (installed capacity)

Algeria has significant wind potential, although spatially heterogeneous. The national wind resource map, established by the National Office of Meteorology, shows that the most favorable regions are the coastline, the High Plateaus, and to a lesser extent, the South of the country [8]. Average annual wind speeds can exceed 6 m/s at 50 m height, which is generally considered commercially attractive for wind projects [8]. The national renewable energy initiative aims to increase wind power by 5 GW by 2035 [9]. The Kabertene wind farm near Adrar is the most advanced one. It has a capacity of 10 MW and powers the local grid in the southern region. Future projects, such as the Steppe wind complex, plan to install hundreds of MW across several sites (Tipaza, Adrar, Tamanrasset) to diversify the national energy mix and reduce natural gas consumption in electricity production.

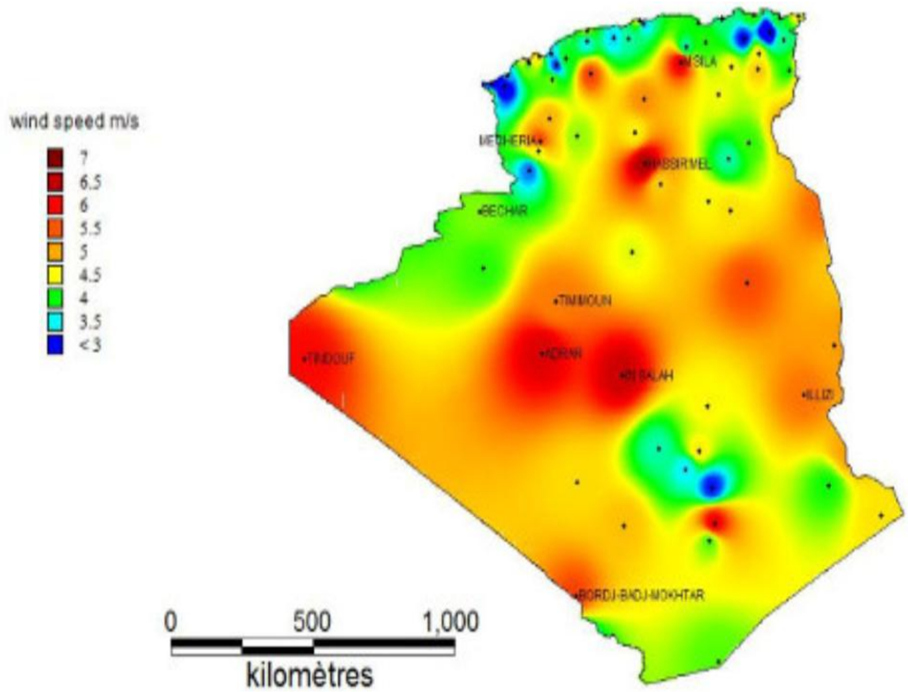

Fig. 2.4 - Algeria's wind resource map at 50 m height, indicating average annual wind speed (m/s) with the most favorable regions (coastline, High Plateaus) [8]

2.6 Advantages and Disadvantages: A Critical Analysis

Advantages:

- **Environmental**: No greenhouse gas emissions or atmospheric pollutants during operation. Direct contribution to the reduction of climate change.
- **Economic**: Wind kWh cost (LCOE) has become competitive with fossil fuels in many regions [1]. It creates local jobs in construction, operation, and maintenance.
- **Energy Security**: Less reliance on fossil fuel imports.
- **Land Use**: Can be used for both farming and raising animals on the same land.

Disadvantages:

- **Intermittency and Variability**: The amount of wind that is available affects production, so backup methods (like gas plants and hydro) or storage are needed to keep the grid balanced.
- **Visual and Noise Effects:** Wind farms can change the look of an area and make noise, but new technologies have made aerodynamic noise much less of a problem.
- **Wildlife Impact**: Birds and bats are at risk of collision, which requires impact assessments and mitigation measures (such as temporary shutdown during migration periods).
- **Cost of Initial Investment:** Very high, but operating costs are low.

2.7 Standards and Regulations

There are strict international rules for the design, installation, and operation of wind turbines. The IEC 61400 series from the International Electrotechnical Commission [10] is the most important set of these rules. This series includes:

IEC 61400-1: What we need to do to design onshore wind turbines.

IEC 61400-11: Measuring sound levels.

IEC 61400-12-1: Testing for power performance.

IEC 61400-21: describing the quality of the electricity supplied to the system.

In practice, standards influence the design process: site wind class selection and load cases (IEC 61400-1), noise compliance constraints affecting layout/setback distances (IEC 61400-11), verification of the power curve and AEP estimation methodology (IEC 61400-12-1), and grid-integration requirements such as power quality and fault behavior for connected systems (IEC 61400-21).

We must adhere to these standards in order to obtain the necessary permissions and certifications and to ensure that installations are secure, dependable, and compatible with other systems.

2.8 Case Study: Small Wind Turbine Installation for an Isolated Site

Context: Figuring out how big a system needs to be to power a pumping station and a small technical building on a remote farm near Tamanrasset. The average use is thought to be 15 kWh per day.

Sizing: The average speed of the wind in the area is 5.5 m/s. A 5 kW wind turbine model is chosen, such as a permanent magnet direct-drive model. A 20 kWh (usable) battery bank and MPPT charge controller are sized to keep the system running on its own during calm times.

System Architecture: The system is configured as a **standalone hybrid**. The wind turbine charges batteries via the controller. A 5 kVA standalone inverter converts battery DC current to 230 V AC to power loads. A backup diesel generator is provided for extended low-wind periods.

Assumptions: daily load = 15 kWh/day; required autonomy = 1–2 days; battery DoD limit = 80% (Li-ion) or 50% (lead-acid); inverter efficiency = 92–96%; controller + wiring losses = 3–8%; availability factor = 0.95; temperature/derating considered. The selected battery usable capacity is checked against autonomy and DoD constraints.

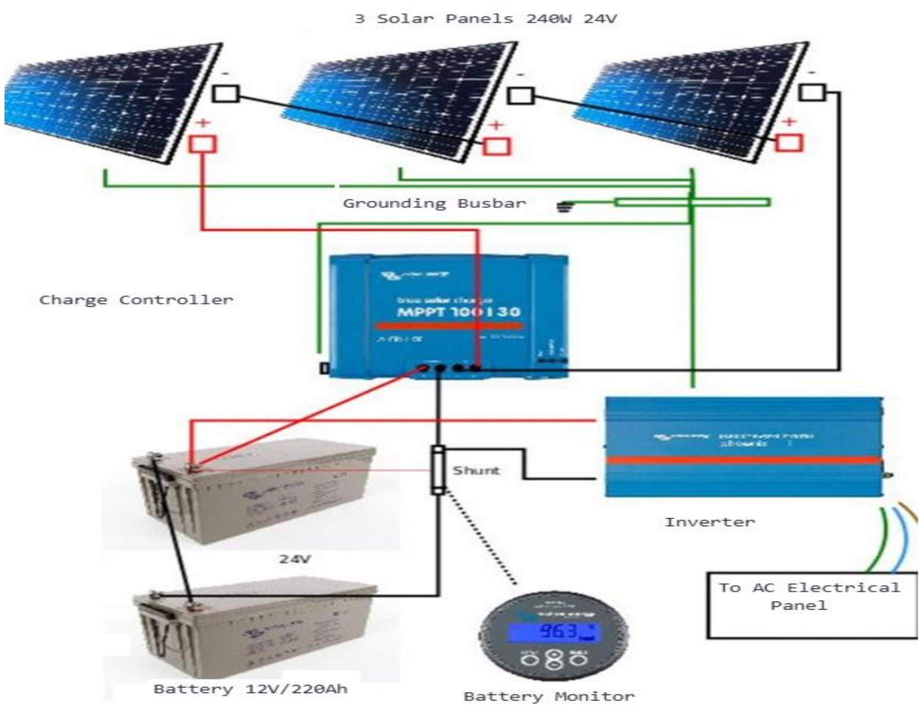

Fig. 2.5 - Synoptic diagram of a standalone wind installation for isolated site, integrating wind turbine, MPPT controller, battery bank, and inverter [15]

Simplified Economic Analysis:

The investment Cost (CAPEX) is ~€45,000 (wind turbine, tower, batteries, inverter, installation).

The annual operating cost (OPEX) is about €500, which includes maintenance and replacing part of the battery every 5 to 7 years.

When compared to the "diesel-only" option, the wind system has higher capital costs (CAPEX), but it generates fuel and operating costs (OPEX) over the medium term. The return on investment is expected to be between 8 and 10 years, not counting the good effects on the environment.

2.9 Conclusion

Wind energy is a well-known, cost-effective technology that is necessary for the transition to clean energy. Its principle, which is based on aerodynamics and electromagnetism, has been improved to make machines that work very well [16-20].

Algeria has a lot of potential, especially along the coast and in the High Plateau. For this sector to be successful, the national program must be carried out well, local maintenance skills must be developed, and this variable production must be smartly added to the national electricity grid. To deal with problems caused by intermittency and social acceptance, careful planning and clear communication are needed . Although wind energy has considerable potential, its intermittent nature and dependence on weather conditions necessitate adapted integration strategies within modern electrical systems.

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KEY POINTS TO REMEMBER

Fundamental Law: Recoverable wind power follows $P = \frac{1}{2}\rho S V^3 C_p$ where ρ is air density, S swept area, V wind speed, and C_p power coefficient.

Betz Limit: No wind turbine can convert more than $\frac{16}{27}$ (=59.3%) of wind kinetic energy to mechanical energy.

Architecture of a Horizontal Axis Wind Turbine:

Rotor (blades and hub)

Nacelle (gearbox, generator, and yaw system)

Tower (support structure)

Systems for control and safety

Power Curve That Is Typical:

Cut-in speed: 3 to 4 m/s

Rated speed: 12 to 15 m/s (highest power)

Cut-out speed: 25 m/s (to shut down for safety)

The Wind Potential in Algeria:

Good areas: the coast and the high plateaus

Average speeds over 6 m/s at a height of 50 m

5 GW by 2035 is the goal of the national program.

No emissions while in use

LCOE is as cheap as fossil fuels.

Job creation in the area.

Works well with farming land use

Problems:

Intermittency and variability

Effects on sound and sight

Risks to birds

A lot of money up front

Important Standards: IEC 61400 series (safety, design, performance)

SELF-EVALUATION

QUESTION 1: Why does the cube of wind speed affect wind power?

SOLUTION:

The power available in wind is proportional to the cube of wind speed because wind power depends on:

The kinetic energy of moving air

The mass flow rate of air passing through the turbine

QUESTION 2: What does the Betz limit (59.3%) mean in real life?

SOLUTION:

The Betz limit says that a wind turbine can't get more than 59.3% of the kinetic energy in the wind, even in the best conditions (perfect flow, no friction). In real life, modern turbines get 45–50%. This basic physical limit makes it possible to test how well a real machine works.

QUESTION 3: What are the three main parts of a horizontal axis wind turbine, and what do they do?

SOLUTION:

Rotor (blades + hub): captures the kinetic energy of the wind and transforms it to mechanical and rotational one.

Nacelle: This is where the control systems and conversion systems (gearbox, generator) are.

Tower: A support structure that raises the rotor to heights where the winds are stronger and more stable.

QUESTION 4: Why is it important to have space between the turbines in a wind farm?

SOLUTION:

When there isn't enough space between turbines, they cause "wake effects," which means that the turbine upstream changes the flow of wind, slowing it down and making it more turbulent for machines downstream. This makes them work less and puts more stress on the machines. The empirical rule says that spacing should be about 5–9 rotor diameters in the prevailing wind direction.

QUESTION 5: Name two important IEC standards for wind energy and explain what they are for.

SOLUTION:

IEC 61400-1: Requirements for the design of onshore wind turbines (loads, safety, and reliability).

IEC 61400-12-1: A way to test how much power a wind turbine can produce.

IEC 61400-21 (bonus): Characterization of power quality injected into the grid.

QUESTION 6: Why does offshore wind present greater potential than onshore wind?

SOLUTION:

Winds at sea are stronger and more steady (the surface is less rough).

Ability to put in more powerful machines (which got rid of land transport limits).

Fewer social acceptability constraints (distance from settlements).

Considerable available area.

QUESTION 7: What are the three characteristic speeds of a wind turbine power curve?

SOLUTION:

1. **Cut-in speed**: 3- 4 m/s, below which production is zero.
2. **Rated speed**: 12-15 m/s, where the machine delivers maximum power.
3. **Cut-out speed**: 25 m/s, when the turbine shuts down to prevent structural damage.

MULTIPLE-CHOICE QUESTIONS

QUESTION 1: The maximum theoretical power coefficient of a wind turbine (Betz limit) is:

A. 50%
B. 59.3%
C. 75%
D. 100%

SOLUTION: B

QUESTION 2: In the wind power formula $P = \frac{1}{2}\rho S V^3 C_p$, the term S represents:

A. Blade surface area
B. Swept area of the rotor
C. Tower cross-section
D. Site area

SOLUTION: B

QUESTION 3: Algeria's region with strongest wind potential is:

A. The Sahara
B. Kabylie
C. The coastline
D. The Aurès

SOLUTION: C

QUESTION 4: Which system allows the turbine to face the wind?

A. Pitch control system
B. Gearbox
C. Yaw system
D. MPPT regulator

SOLUTION: C

QUESTION 5: The speed at which a 2 MW wind turbine reaches its rated power is typically:

A. 5 m/s
B. 8 m/s
C. 12-15 m/s
D. 20 m/s

SOLUTION: C

QUESTION 6: To reduce wake effects between turbines, they should be spaced about:

A. 2–3 rotor diameters

B. 5 to 9 rotor diameters

C. 10 to 15 rotor diameters

D. 20 rotor diameter

SOLUTION: B

CHAPTER 3 : HYBRID SYSTEMS

3.1 Introduction to Hybrid Energy Systems

To overcome variability and ensure continuity of supply, hybrid systems combining several energy sources and storage devices constitute a relevant technological solution. The energy transition depends on the large-scale use of renewable energies (RES), which are hard to work with because they are not always available and can change. To ensure a reliable and stable electricity supply, it is imperative to move beyond the single-source production model. Hybrid systems are defined as the intelligent combination of multiple energy sources, often renewables, complemented by storage systems and/or backup generators. Their goal is to compensate for the individual weaknesses of each source [1]. This chapter aims to explore the hybrid system concept before focusing on an emerging and promising technology for stable production: hydrokinetic energy. We will analyze its principles, different architectures, key players, and challenges to address.
A tidal-stream turbine (hydrolienne in french) converts the kinetic energy of marine or river currents into electricity.

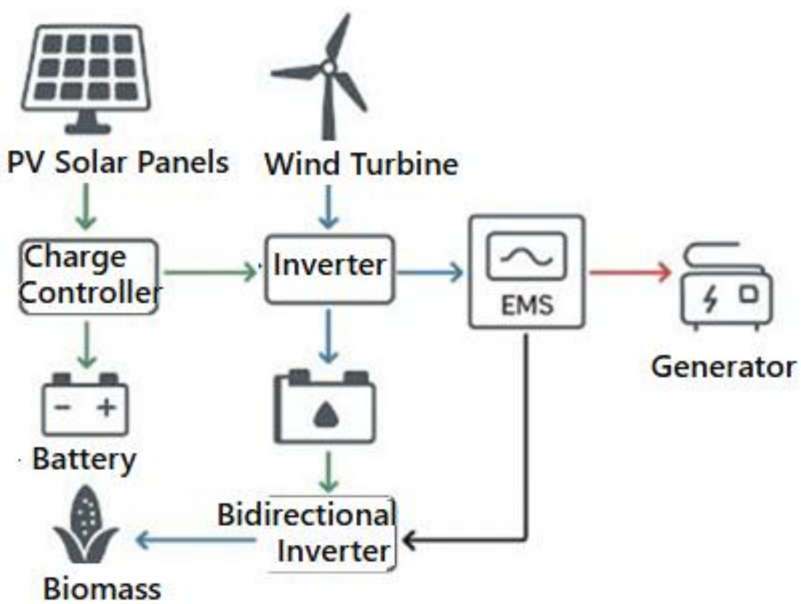

Fig. 3.1 - Conceptual diagram of a complex hybrid system integrating solar, wind, biomass, battery storage, and backup electromechanical generator [1].

3.2 Typology and Architectures of Hybrid Systems

Hybrid systems can be classified according to several criteria: their scale, grid connection mode, and component nature.

3.2.1 Classification by Scale and Application

Autonomous off-grid hybrid systems

Designed to provide power to locations that are not connected to the national grid.

Applications: Rural electrification (villages, farms), telecom stations, mountain shelters.

Typical Architecture: PV + wind + batteries + gas/diesel/biogas generator.

The generator serves as backup for extended periods of bad weather...

Grid-Connected On-Grid Hybrid Systems

They inject their production into the public grid. The objective is to maximize self-consumption and sell surplus.

Applications: Power plants, industrial or commercial installations.

A typical architecture includes PV, wind, and a storage system (like batteries or a flywheel) to help with production and provide grid services.

Micro-hybridization of small-scale hybrid systems

Uses: hybrid cars and power for autonomous sensors.

Common architecture: fuel cell and supercapacitors.

3.2.2 Key Components and Role in Hybrid Systems

In addition to primary generators like PV and wind, the following parts are also very important:

Energy Storage System: Backup generator: Usually a diesel, biogas, or hydrogen generator that operates as a backup and ensures supply security.

Batteries (Lead-acid, Li-ion): Storage for a short or medium amount of time (hours or days). Li-ion batteries are more expensive, but they have a higher energy density and last longer [2].

Long-term or seasonal storage of hydrogen (electrolyzer + fuel cell). Electrolysis ‘s output is hydrogen. a fuel cell turns the hydrogen back into electricity.

Pumped hydro storage (STEP) is used for for large grid-scale power and energy capacities [2].

This is usually a diesel, biogas, or hydrogen generator that works as a backup. Checks to see that the supply is safe.

The hybrid regulator and inverter are the system’s brains. It is the control system between sources, loads, and storage system.

Energy Management System (EMS): A sophisticated piece of software that uses predictive algorithms (like weather and load) to make sure the system works as well as it can in real time.

Table 3.1 - Comparison of different storage technologies for hybrid systems [2,3].

Technology	Energy Density (Wh/kg)	Lifespan (cycles)	Response Time	Cost (€/kWh)	Typical Applications
Lead-Acid Battery	30–50	500–1500	Seconds	100–200	Autonomous systems, startup
Li-ion Battery	100–265	1000–6000	Milliseconds	200–500	Electric vehicles, grid storage
H_2 Fuel Cell	500 (for H_2)	20,000 h	Seconds–Minutes	High CAPEX	Long-term storage, transport
Flywheel	5–100	100,000	Milliseconds	500–2000	Frequency smoothing, power quality
Supercapacitors	1–10	500,000	Milliseconds	500–10,000	Power peaks, fine regulation

3.3 Operating principle of a tidal-stream turbine (hydrolienne): fundamentals and potential

Among marine energies, hydrokinetic stands out for its ability to provide predictable and stable production. A hydrokinetic turbine is an underwater turbine that converts the kinetic energy of marine currents or rivers into electricity.

3.3.1 Physical Principles and Advantages

The basic principle is similar to wind power, but applied to water, a medium 800 times denser than air. The recoverable power P by a hydrokinetic turbine with swept area S in a current of velocity V is given by the fundamental equation:

$$P = \frac{1}{2}\rho S V^3 C_p \qquad (3.1)$$

(ρ = seawater density 1025 kg/m³, Cp = performance coefficient).

This high density gives hydrokinetic energy decisive advantages:

Exceptional predictability: Marine currents are induced by tides, governed by the gravitational cycles of the Moon and Sun. Production is therefore predictable over decades [4].

High power density: At equal velocity, a hydrokinetic produces about 800 times more power than a wind turbine of the same diameter.

Low visual impact: Machines are underwater.

Stable and steady production: Tidal currents can go in both directions and can be used in both directions.

3.3.2 Global Potential and Challenges

There is a lot of potential for hydrokinetic energy around the world. It is estimated to represent a production capacity of around 100-120 GW worldwide, with particularly strong potential in Europe (especially UK and France), Asia, and North America. For Algeria, potential is limited in the Mediterranean where tides are weak, but studies could identify specific high-current sites [5]. Global potential estimates vary widely depending on whether they refer to theoretical, technical, or economically exploitable potential, reported ranges should preferably be tied to a specific source, region scope, and year.

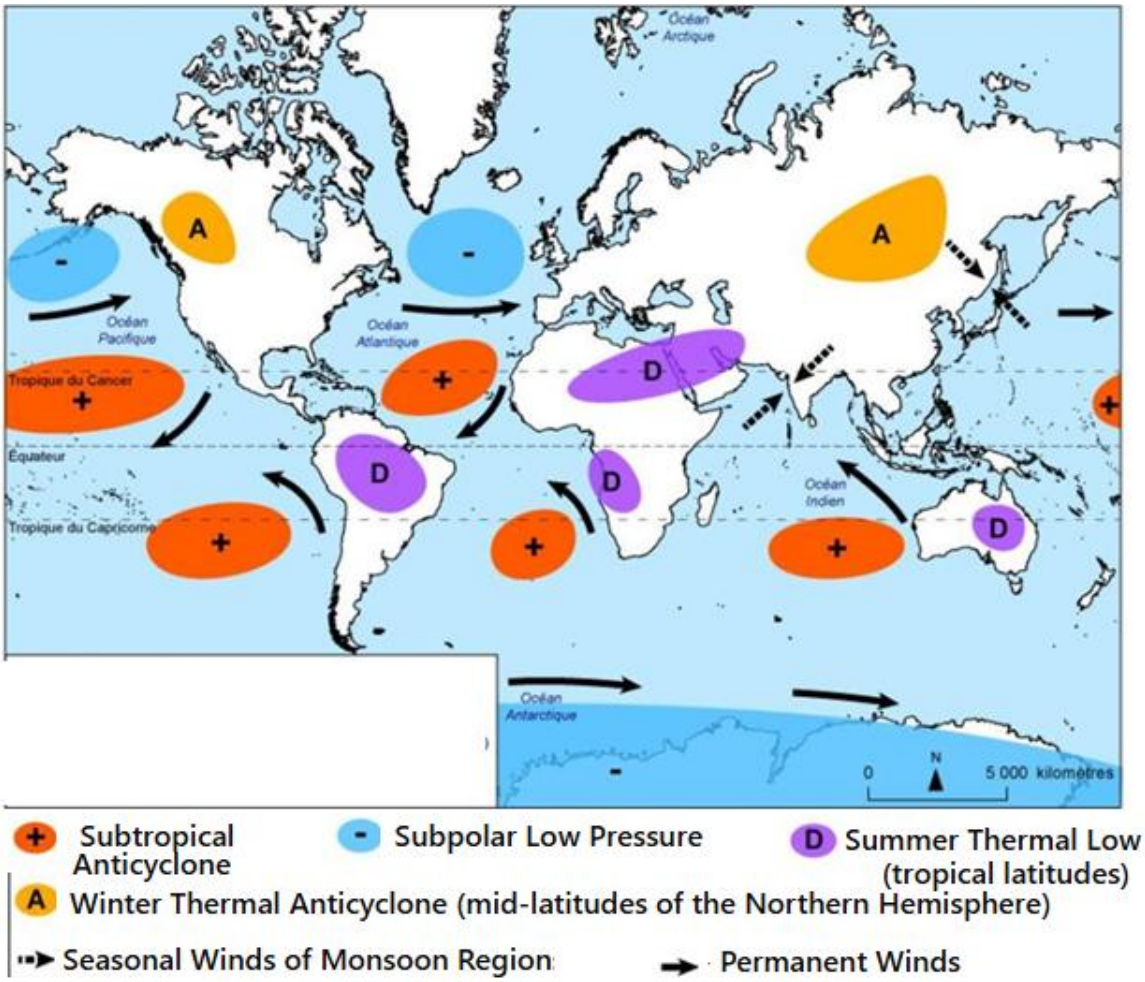

Fig. 3.2 - World map of marine current energy potential showing the most favorable zones for hydrokinetic deployment [5].

3.4 Types of tidal-stream turbines

The sector is still in pre-commercialization phase, leading to diverse technological concepts, mainly classified by rotation axis.

3.4.1 Horizontal Axis Hydrokinetics (HAHT)

Most common, based on wind turbines. The rotation axis is parallel to the direction of the current.

Advantage: The technology is well-developed, and it works very well in the air.

Disadvantages: The yaw system needs to follow the bidirectional current.

Some examples are SIMEC Atlantis (the MeyGen project) and Sabella.

3.4.2 Vertical Axis Hydrokinetics (VAHT)

The axis of rotation is at a right angle to the current. Blades spin no matter which way the flow goes.

Simple mechanics, surface generator, works in any direction, and easier to maintain.

For disadvantages: Generally lower efficiency than horizontal axis, difficult startup.

Examples: Darrieus or Gorlov-type turbines.

3.4.3 Bio-Inspired Oscillating Foil Systems

Radically different approach, bio-inspired by fish swimming (tuna). Foil oscillates up/down via vortices, motion converted to electricity.

Advantages: Very high efficiency potential, reduced marine life impact.

Disadvantages: Less mature, complex mechanical conversion.

Example: BioSTREAM technology by BioPower Systems.

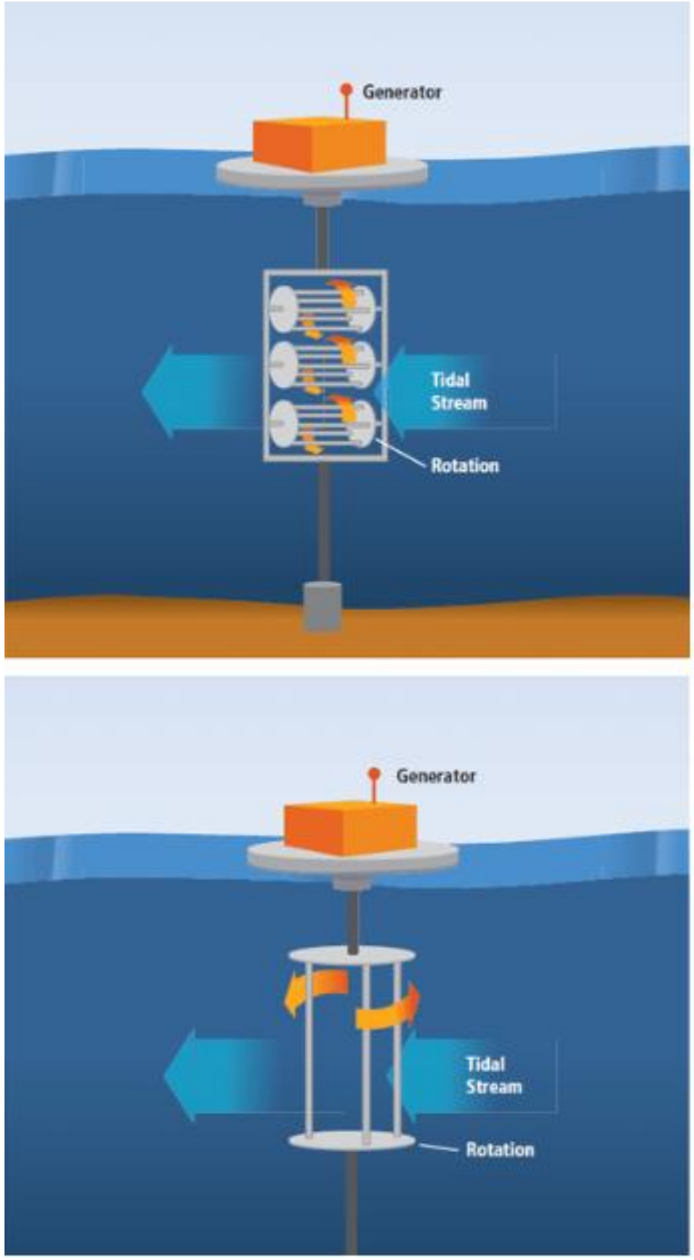

Fig. 3.3 - Different architectures [6].

3.5 Operators/industrial players and flagship tidal-stream projects

The hydrokinetic industrial landscape is dynamic, mixing innovative startups and major energy groups.

3.5.1 Main Industrial Players

SIMEC Atlantis Energy (UK): Sector leader, MeyGen project developer.

Orbital Marine Power (UK): Pioneer of high-power floating horizontal axis hydrokinetics (O2, 2 MW).

Sabella (France): Develops hydrokinetics for French sites, especially Brittany.

Andritz Hydro Hammerfest (Germany/Norway): Develops horizontal axis hydrokinetics.

3.5.2 Flagship Projects Worldwide

MeyGen Project (Pentland Firth, Scotland): World's first large-scale commercial hydrokinetic farm. Phase 1 (2016): 4 turbines × 1.5 MW = 6 MW capacity. Targets 398 MW total [7].

Paimpol-Bréhat Project (France): Led by EDF, tested 1 MW OpenHydro horizontal axis turbine in real conditions. It provided valuable feedback on technical difficulties encountered in real sea conditions.

Jindo Pilot Farm in South Korea uses hydrokinetic technologies with vertical axes.

Fig. 3.4 - Orbital Marine Power's floating O2 hydrokinetic (2 MW) during deployment in Scotland [7].

3.6 Technical, Economic, and Environmental Challenges

Hydrokinetic energy has significant potential but still faces major barriers to large-scale deployment.

3.6.1 Technical Challenges

Hostile Environment: Machines that are exposed to saline corrosion, biofouling, strong currents, and high hydraulic pressure. Materials and coatings need to be very strong.

Maintenance: Complex, costly operations dependent on weather windows (difficult winter conditions).

Connection and Anchoring: Submarine cabling for grid connection is heavy investment. Seabed anchoring must withstand considerable forces.

3.6.2 Economic Challenges

Investment Costs (CAPEX): Very high due to technology youth, installation complexity, marine component costs.

Levelized Cost of Energy (LCOE): Though decreasing, remains higher than offshore wind and solar. To lower costs, further mass production and industrialization are necessary [8-11].

Financing: Some investors don't want to take on a lot of risk.

3.6.3 Environmental and Social Challenges

Marine Life Impact: Main risks: collisions with marine mammals/fish, underwater noise pollution, electromagnetic field effects from cables. Strict environmental studies/monitoring essential [9-13].

Usage Conflicts: Coexistence with professional fishing, navigation, military activities.

Social Acceptability: Though low visibility, projects may raise local concerns about marine ecosystem/subsea landscape impacts.

3.7 Conclusion and Perspectives

Hybrid systems are the way of the future for decentralized, reliable energy production [14]. They offer a real solution to the problem of intermittency by smartly combining different types of renewable energy and storage. Hydrokinetic energy is a renewable source with a lot of potential. It is very predictable and has a high power density. If it can get past the current techno-economic problems with new ideas, standardization and targeted political support, it could be a big part of the energy mix in coastal areas that benefit from strong marine currents. For countries like Algeria, hydrokinetic energy is not an immediate priority, but technology monitoring remains strategically important for the future. The efficiency of a hybrid system thus relies on the complementarity of the sources and on optimized management of energy flows, particularly when one of the main sources is of solar origin.

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CHAPTER 3 SUMMARY - HYBRID SYSTEMS & HYDROKINETIC ENERGY

Hybrid System Definition: Combines several energy sources, storage, and a backup generator to make sure there is always a reliable supply, even when renewables are not always available.

Main Hybrid Types:

Off-grid (isolated sites): PV + wind + batteries + diesel generator.

On-grid (network participation): PV + wind + storage...

Micro-hybridization (small scale): fuel cell + supercapacitors.

Critical Storage Role: Stability cornerstone - Li-ion batteries, hydrogen, flywheels.

Hydrokinetic Energy: Exploits marine/tidal currents. Advantages: very predictable and has a high energy density. Barriers: corrosion, high costs, and potential effects on marine life. Perspectives: hybridization combined to storage is the solution to a stable decarbonized grid.

REVIEW POINTS

Off-grid means being completely independent, while on-grid means being connected to the grid. On-grid = network services optimization.

Thermal generator precise role in hybrids: Security backup during extended no-wind/no-sun periods.

Storage technologies: Batteries (short-term). Hydrogen (long-term). STEP (network inertia support).

Hydrokinetic constraints: Underwater noise, cable electromagnetism, fishing/navigation conflicts.

Typical PV+wind+batteries architecture: Master production flows, DC regulation, storage, AC injection.

SELF-ASSESSMENT

QUESTION 1: Why are hybrid systems indispensable for renewable energies?

SOLUTION: Because they compensate the natural intermittency of PV and wind by combining multiple sources + storage, ensuring stable supply.

QUESTION 2: Cite two typical Off-Grid hybrid architectures.

SOLUTION: PV + wind + Batteries + Generator; PV + Batteries for isolated telecoms.

QUESTION 3: Why is hydrokinetic very predictable?

SOLUTION: Because tidal currents follow regular astronomical cycles → very reliable prediction.

QUESTION 4: Name two technical problems that hydrokinetic systems face.

Corrosion from a harsh marine environment; high costs of installation and maintenance.

QUESTION 5: What does storage do in a hybrid system?

SOLUTION: Store extra, make production run smoothly, and make sure the network stays stable and connected.

MULTIPLE CHOICE QUESTIONS

QUESTION 1: A mixed system is:

A. System that only uses solar energy

B. A combination of multiple energy sources and storage

C. System without rules

D. Gas turbine and alternator

SOLUTION: B.

QUESTION 2: Off-Grid systems are used for:

A. Big plants that are connected to the grid

B. Buildings for businesses

C. Electrification of rural areas that are not connected to the grid

D. Dams for water

SOLUTION: C.

QUESTION 3: Storage is important because:

A. Completely replaces panels

B. Makes up for the fact that renewable energy isn’t always available

C. Lowers the power in the grid

D. Makes the power factor higher

SOLUTION: B.

QUESTION 4: Hydrokinetic is different because of:

A. Very cheap

B. Very predictable

C. No production in the winter

D. No effect on the environment

SOLUTION: B.

QUESTION 5: Main environmental risk from hydrokinetics:

A. Pollution in the air

B. Collisions with marine life

C. Radioactivity

D. Cutting down trees

SOLUTION: B.

QUESTION 6: Example of an on-grid hybrid:

A. PV, wind, batteries, and the grid

B. PV and animal power

C. Only diesel

D. Only the hydro turbine

SOLUTION: A.

QUESTION 7: Micro-hybridization use:

A. Plants with 500 MW

B. Cars that run on both gas and electricity

C. Dams on rivers

D. National grids

SOLUTION: B.

CHAPTER 4 : SOLAR PHOTOVOLTAIC ENERGY

4.1 Introduction

Among the renewable technologies that can be integrated into hybrid architectures, photovoltaic energy stands out for its modularity, technological maturity and strong dynamic of deployment on a global scale.
Solar photovoltaic (PV) energy represents one of the cornerstones of the global energy transition. Its principle of direct conversion of solar radiation into electricity, without moving parts and without emissions, makes it a particularly attractive technology. The sector has experienced exponential growth over the last decade, with drastic cost reductions of over 80% since 2010, making solar electricity competitive, and even cheaper than fossil fuels in many sunny regions [1].
This chapter aims to provide a comprehensive understanding of photovoltaic technology, from cell physics to system integration. We will cover the conversion principle, Algerian solar potential, cell technologies, installation components, MPPT optimization strategies, safety standards, and illustrate everything with a concrete case study.

4.2 Solar Potential in Algeria: Exceptional Resource

Algeria possesses one of the world's most important solar resources. Its territory benefits from average annual insolation exceeding 2,000 kWh/m² across nearly the entire country, reaching 2,650 kWh/m² in the Sahara [2]. Sunshine duration frequently exceeds 3,000 hours per year. This abundance positions Algeria strategically for massive solar energy development.

The National Renewable Energy and Energy Efficiency Program (PNEREE) aims to install 13,575 MW of electricity production capacity from renewable sources by 2035, with a significant portion (~6,000 MW) dedicated to solar photovoltaic [3]. This ambitious goal demonstrates the will to diversify the energy mix and exploit this indigenous resource.

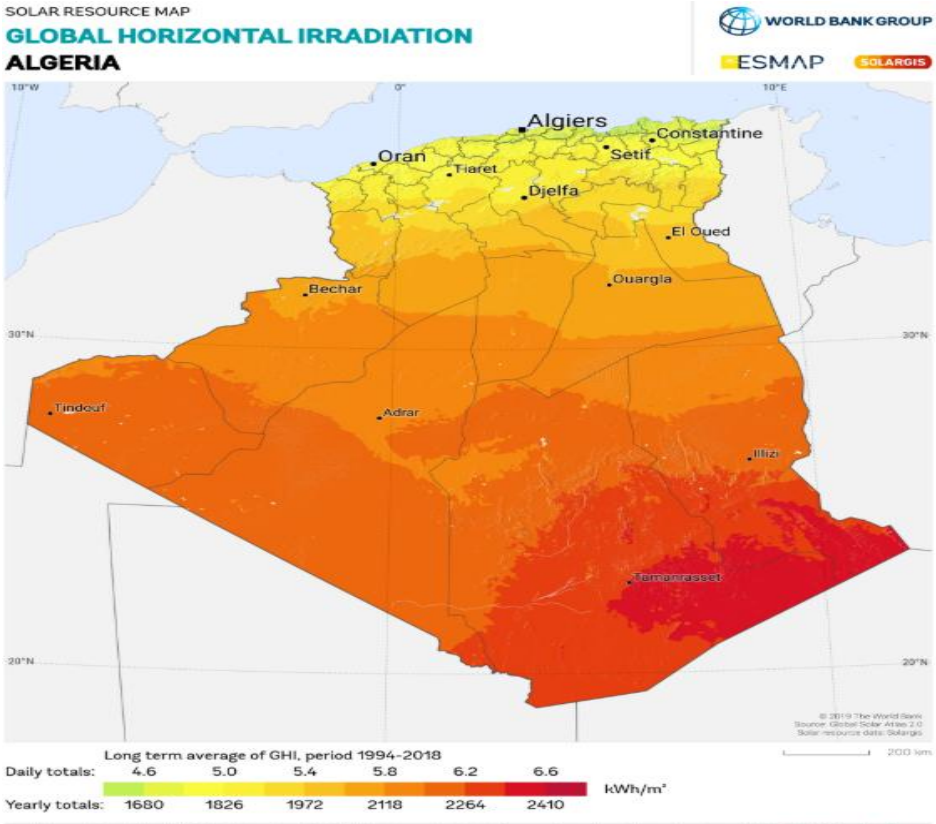

Fig. 4.1 - Map of annual global horizontal irradiation (GHI) in Algeria (kWh/m²/year) showing the country's exceptional potential, particularly in Saharan regions [2].

4.3 Physics of the Photovoltaic Cell and Technologies

4.3.1 Fundamental Principle: Photovoltaic Effect

Edmond Becquerel discovered the photovoltaic effect in 1839. It is a physical phenomenon that lets light energy be turned directly into electrical energy. Silicon is the most common type of semiconductor material that this happens in. There are three main steps in the process.

Getting and Making Electron-Hole Pairs: A photon with higher energy than the semiconductor's bandgap will be absorbed. It transfers its energy to an electron in the valence band. This electron is excited and moves to the conduction band, leaving behind a hole that is positively charged. This makes an electron-hole pair.

Charge Separation: An internal electric field at a PN junction makes this separation possible. This junction is made when P-doped semiconductor (which has too many holes) and N-doped semiconductor (which has too many electrons) touch each other. The electric field pushes holes toward the P region and electrons toward the N region.

Current Collection: When electrons and holes reach their metal contacts (front and back), they can flow through an outside circuit, creating a steady flow of electricity.

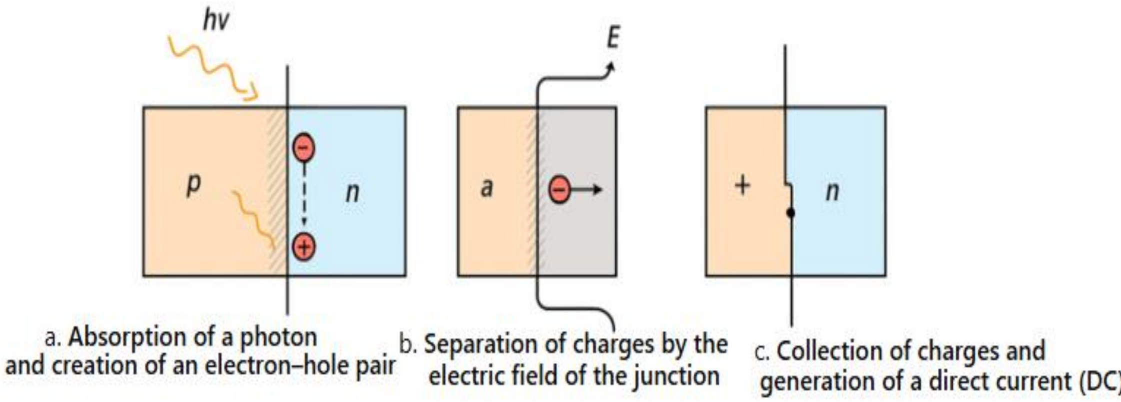

Fig. 4.2 - Principle diagram of the photovoltaic effect in a PN junction: a) photon absorption and electron-hole pair creation, b) charge separation by electric field, c) collection and current generation [4].

4.3.2 Photovoltaic Cell Technologies

Silicon is the most important material in technology, but new ones are coming out all the time.

- Crystalline silicon (c-Si) accounts for about 95% of the PV module market [5].

Monocrystalline Silicon (mono-Si): This type of silicon is made from just one crystal of silicon (Czochralski method). Dark blue-black color all over, with cut corners.

Advantage: Most efficient (22–25% in the lab, 20% in business).

Disadvantages: It costs more to make.

Polycrystalline Silicon (multi-Si): This is made by melting and casting pieces of silicon.

Advantage: Lower cost of making.

Disadvantages: Less efficient (16–18% commercial), blue color with a grainy look.

Thin-film technologies have a market share of about 5%.

Cadmium Telluride (CdTe) is the best thin-film material. Good efficiency (18–20% module), low cost of production, but it uses poisonous cadmium.

Amorphous Silicon (a-Si): Not very efficient (6–8%), but works well in diffuse light and is flexible.

Copper-Indium-Gallium-Selenide (CIGS): High potential efficiency (20% in the lab), but hard to make.

Emerging technologies

Perovskite Cells: Lab efficiencies over 25%, very low costs of production, but problems with stability and lead toxicity.

Stacking two cells (e.g. perovskite over silicon) yields tandem devices that capture a wider part of the solar spectrum, with record efficiencies exceeding 33% [6].

Organic Photovoltaic Cells (OPV): They are light, flexible, and semi-transparent, but their efficiency and lifespan are limited.

Table 4.1 - Comparison of main commercial photovoltaic technologies [5,6].

Technology	Module Efficiency (Commercial)	Advantages	Disadvantages
Monocrystalline Silicon	16.5–19%	High efficiency, long lifespan	Highest cost
Polycrystalline Silicon	15–18%	Good value for money	Lower efficiency, less aesthetic (poly largely phased out)
CdTe Thin-Film	~17–19%	Very low cost, good high-temp performance	Cd toxicity, Te supply constraints
CIGS Thin-Film	~15–18%	High potential, flexible	Complex manufacturing process
Perovskites (R&D)	~24% (mini-module record, not mass commercial)	Very low cost potential, very high efficiency potential	Stability, lead toxicity concerns

4.4 From Module to System: Components and Characteristics

4.4.1 The Photovoltaic Module

A single cell produces low voltage (~0.6V) and limited power. To obtain usable voltage and power, cells are connected:

- In series to increase voltage.
- In parallel to increase current.

A module/panel is an assembly of typically 60, 72, or 144 cells encapsulated between tempered glass (front) and polymer backsheet, framed in aluminum. Bypass diodes are connected in antiparallel with groups of cells to limit reverse bias and avoid hot-spots under partial shading.

The I-V curve (Current-Voltage) is the most important electrical property of a module.

Important points:

Short-Circuit Current (Isc): The most current that can flow when the voltage is zero.

Open-Circuit Voltage (Voc): The highest voltage when there is no current.

Maximum Power Point (Pmax or MPP): The point (Vmp, Imp) where the most power is delivered.

a) I-V characteristic

b) P-V characteristic

Fig. 4.3 - Characteristic I-V (current-voltage) and P-V (power-voltage) curves of a photovoltaic module showing the maximum power point (MPP) [7].

4.4.2 Mounting Structures

Modules must be fixed on robust structures and optimally oriented.

Fixed Structures: Azimuth and tilt are fixed. In Algeria, for maximum annual production: due South orientation, ~30° tilt optimal.

Tracking Systems: Move modules around to follow the sun.

1-axis trackers (east-west) can make 15–25% more.

2-axis trackers (azimuth + elevation) give a 25–35% gain, but they cost more to buy and keep up.

4.5 PV Wiring, Connectors, and Protection Devices (DC/AC)

4.5.1 Wiring architecture (strings, combiner, polarity):

Photovoltaic interconnection is typically organized into strings (modules connected in series to increase DC voltage) and, when needed, several strings connected in parallel to increase current. Each string must respect inverter limits (maximum DC voltage and maximum input current), and the design must keep cable lengths reasonable to reduce resistive losses. Correct polarity management and clear string identification are essential because reverse polarity can damage equipment and create safety hazards during commissioning and maintenance.

4.5.2 Connectors and junction boxes (connectique)

Most PV modules come with factory-installed junction boxes and standardized DC plug connectors (often MC4/MC4-type) designed for outdoor, IP-rated connections.
To prevent overheating and DC arcing, connectors must be fully inserted and locked, with correctly matched contacts and proper crimping.
As a safety practice, avoid cross-mating connectors from different manufacturers even if labeled 'MC4-compatible', because it may compromise contact quality, certification compliance, and long-term

reliability; use matched connector pairs validated by the manufacturer and applicable standards. Good practice also includes routing and fixing cables so connectors are not left under permanent tensile stress and so the cable path avoids sharp edges, UV exposure, and water accumulation points.

4.5.3 DC protections (fuses, isolator, SPD, earthing)

A PV generator needs dedicated DC-side protection, typically including string overcurrent protection (string fuses or string circuit breakers when applicable), a DC isolator for safe maintenance, and DC surge protective devices (SPDs) to limit lightning/switching overvoltages.

Bonding/earthing of metallic module frames and mounting structures reduces electric-shock risk and supports fault clearing through equipotential bonding.

4.5.4 AC protections and grid interface:

On the AC side, the inverter output is protected by an AC circuit breaker, residual current protection (RCD/RCBO where required), and an AC SPD depending on the installation exposure and national rules. Grid-connected systems must also comply with anti-islanding protection and disconnection requirements so that the inverter stops injecting power when the grid is lost. Clear labeling (DC warning signs, isolator positions, and emergency shutdown information) is a simple but critical safety measure for occupants and technicians

4.6 The Inverter: The Power Conditioning System's Main Part

The inverter is the second most important part after the modules. It changes the DC current from the panels into AC that the electrical grid can use.

4.6.1 Responsibilities and Duties

DC-AC conversion: This makes a 50 Hz sine wave by using a pulse width modulation (PWM) and an IGBT/MOSFET transistor bridge.

MPPT Optimization: Uses one or more Maximum Power Point Tracking algorithms to make things work better.

Grid Synchronization: Locks onto the grid's voltage, frequency, and phase.

Safety features: automatic disconnection for grid problems (anti-islanding), surge protection, and monitoring of insulation.

4.6.2 Different Types of Inverters

Central Inverters: One big inverter that powers the whole installation.

Low cost per watt.

Disadvantage: If part of the installation is in the shade, production will go down.

String Inverters: There is one inverter for each string of modules that are connected in series. The most common technology.

Better management of strings on their own.

Microinverters: An inverter is built into each module.

Advantage: Each module can be optimized separately (great for roofs with a lot of angles), very low DC voltage safety, and detailed monitoring.

Drawback: Higher cost up front.

4.6.3 Features and Effectiveness

The efficiency of an inverter is not always the same:

Maximum Efficiency (η_{max}): The highest level of efficiency that can be reached (about 98%).

European Efficiency (η_{euro}): a weighted measure of efficiency that takes into account the normal operating profile. Sign that is more accurate.

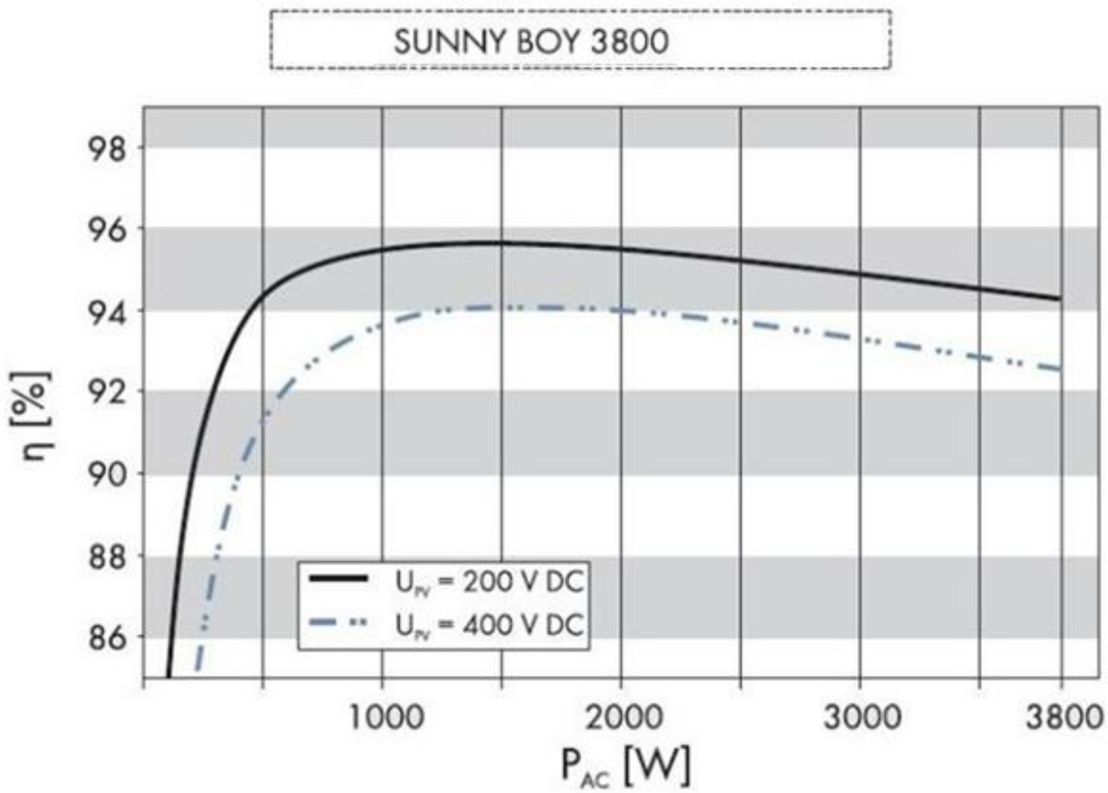

Fig. 4.4 - Typical photovoltaic inverter efficiency curve vs. load percentage, showing maximum and European efficiency [8].

4.7 Optimization: Maximum Power Point Tracker (MPPT)

The MPP of a module changes all the time based on how much light and heat it gets. The job of MPPT is to always look for and follow this point in order to get the most power possible.

Some common MPPT algorithms are:

Perturb & Observe (P&O): This algorithm changes the operating voltage a little bit and watches how it affects power. If power goes up, it keeps going in the same direction.

Incremental Conductance is more stable than P&O and finds the best point by looking at the slope of the P-V curve ($dP/dV = 0$ at MPP).

4.8 Standards and Safety

PV installations are subject to strict standards for people and property safety:

IEC 61215: design qualification (modules).

IEC 61730: module safety (modules).

IEC 62109: inverter safety (inverters).

IEC 61683: inverter efficiency measurement (inverters).

IEC 60364-7-712: PV installation requirements (system/wiring/protection).

4.9 Case Study: 6 kWp Residential PV Installation in Algiers

Context: Family wants to reduce electricity bill and carbon footprint. House in Algiers has 6,000 kWh annual consumption. Roof faces South, 25° pitch, no shading.

Sizing:

Peak power: 6 kWp for self-consumption with surplus injection.

Modules: 16 × 375 Wc monocrystalline silicon modules.

Inverter: 6 kW string inverter with 2 MPPT trackers (2 strings of 8 modules).

Estimated production: 6 kWp × 1,500 kWh/kWp (typical specific yield for Algiers, based on [2,9]) = 9,000 kWh/year.

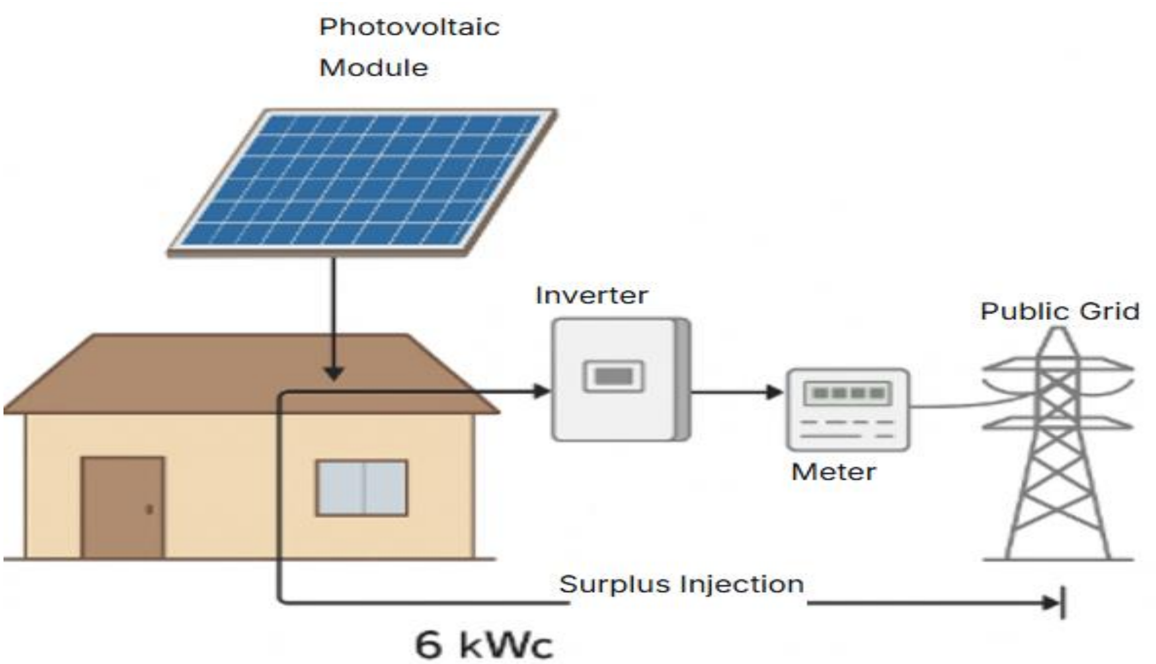

Fig. 4.5 - Synoptic diagram of a 6 kWp residential PV installation in self-consumption with surplus injection [9].

Investment (CAPEX): 90,000 DZD/kWp × 6 kWp = 540,000 DZD.

Annual savings: 6,000 kWh self-consumed × 5 DZD/kWh + 3,000 kWh injected × 3 DZD/kWh = 39,000 DZD/year.

Simple payback: 540,000 ÷ 39,000 = 14 years. Can be reduced by subsidies or electricity tariff increases.

4.10 Chapter Conclusion

Solar photovoltaic energy is a mature [10-20], reliable technology that has become economically viable. It can be used for a wide range of needs, from small off-grid kits to multi-hundred MW power plants, thanks to its direct conversion principle, variety of technologies, and modular installation. For Algeria, solar PV is a very important strategic chance. The combination of great solar resources, costs that keep going down, and ambitious political goals makes it a good time for large-scale deployment. Challenges now lie in developing local industry and maintenance supply chain, adapting the electrical grid to absorb intermittent production, and implementing incentive financing mechanisms for individuals and industries. However, the massive deployment of photovoltaic systems cannot be assessed solely on technical considerations; it also requires rigorous economic and comparative analysis [17-19].

To illustrate the theoretical aspects of this chapter, it is relevant to add a few concrete examples of photovoltaic deployment in the Algerian context, particularly in the Grand Sahara regions [20-24]. The report published by CEREFE indicates that, by the end of December 2023, installed renewable energy capacity had reached 600.9 MW nationwide, including 472 MW excluding hydropower, while official projections announce that the 4,000 MW threshold will be exceeded through the future construction of 21 photovoltaic plants distributed across the country. In southern Algeria, these achievements confirm the strategic importance of the Sahara for large-scale installations, especially since the solar resource there is particularly favorable, with sunshine duration reaching up to 3,900 hours per year in the High Plateaus and the Sahara. For example, the national program already includes photovoltaic solar plants, hybrid installations, and electrification kits for isolated areas, which shows the gradual transition from a demonstration-oriented approach to an industrial-scale deployment strategy. This momentum is also consistent with the actions of CDER, which organizes the International Renewable Energy Days to promote scientific exchange and accelerate the development of clean and sustainable energy sources in Algeria.

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CHAPTER 4 : KEY POINTS TO RETAIN

Cost reduction: 80% since 2010 + competitiveness vs. fossil fuels.

Algeria’s exceptional solar resource: 2,000-2,650 kWh/m²/year irradiation + 3,000 h/year sunshine.

Photovoltaic effect principle:

Photon absorption → electron-hole pair

Separation by PN junction internal field

Current collection at metallic contacts

Cell technologies:

Monocrystalline: best efficiency (20% commercial)

Polycrystalline: cheaper, 16-18% efficiency

Thin-film: CdTe, a-Si, CIGS (flexible, low cost)

Perovskites/tandem: 25% lab, 33% tandem

PV module: Series/parallel cell assembly (typically 60, 72, or 144 cells).

Inverter: DC-AC conversion core. Functions: MLI conversion, MPPT, grid synchronization, protections (anti-islanding, surge...).

MPPT: Maximum power extraction (P&O, Incremental Conductance algorithms...).

Case study: 6 kWp residential installation (16 × 375 Wp) in Algiers, yielding about 9,000 kWh/year under typical performance ratio assumptions.

REVIEW POINTS

GHI vs. actual production difference: GHI = raw potential. Production depends on module, temperature, angle, DC/AC losses.

Exact PN junction function: Doesn’t create energy - separates charges.

Thin-film not necessarily low efficiency: CdTe can reach 19% module efficiency.

European inverter efficiency: Weighted per typical load profile (realistic indicator).

MPPT not magic power booster: Optimizes but doesn’t create extra energy.

SELF-ASSESSMENT

Question1. Why is Algeria ideal for photovoltaics?

SOLUTION: Exceptional solar resource worldwide (2,000-2,650 kWh/m²/year + 3,000 h/year sunshine).

Question 2. What are the three physical steps of PV effect?

SOLUTION: 1) Photon absorption → electron-hole pair,

2) Separation by PN junction internal field,

3) Current collection at metallic contacts.

Question 3. Why connect cells in series in a module?

SOLUTION: To increase module voltage.

Question 4. Cite two monocrystalline advantages.

SOLUTION: High efficiency + long lifespan.

Question 5. What is MPPT's role?

SOLUTION: Continuously search optimal voltage corresponding to MPP to maximize extracted power.

Question 6. Why are microinverters advantageous on complex roofs?

SOLUTION: Individual module optimization (partial shading).

MULTIPLE CHOICE QUESTIONS

Solar PV converts:

A. Heat → electricity

B. Light → electricity via PN effect

C. Wind → electricity

D. Chemical → electricity

SOLUTION: B. Light → electricity via PN effect

Dominant market technology:

A. CIGS

B. Perovskites

C. Crystalline silicon (95% market)

D. Amorphous silicon

SOLUTION: C. Crystalline silicon (95% market)

PV module consists of:

A. Single cell

B. 5 cells

C. Dozens of series/parallel cells

D. Miniature turbines

SOLUTION: C. Dozens of series/parallel cells

Inverter performs:

A. DC-AC + MPPT

B. AC-DC

C. Storage

D. Panel orientation

SOLUTION: A.

Common MPPT algorithm:

A. Fourier

B. P&O

C. Newton-Raphson

D. PID

SOLUTION: B.

Major microinverter advantage:

A. Very low cost

B. Module-by-module optimization

C. No MLI operation

D. Temperature-independent production

SOLUTION: B. Module-by-module optimization

Expected production 6 kWp system Algiers:

A. 2,000 kWh/year

B. 6,000 kWh/year

C. 9,000 kWh/year

D. 20,000 kWh/year

SOLUTION: C.

CHAPTER 5: PANORAMA OF OTHER RENEWABLE ENERGY SOURCES

5.1 Introduction

It becomes essential to examine techno-economic indicators in order to objectively assess the competitiveness of different electricity production sectors. The global energy transition cannot rest on a single miracle technology. It needs a variety of renewable solutions in its portfolio, each with its own advantages, disadvantages, and areas of use. In addition to solar photovoltaic and wind power, which are growing very quickly, other mature or new sectors are helping or being asked to help decarbonize the energy mix.
This chapter's goal is to give a full and critical picture of these other sources of renewable energy. We will do a synthetic review of the main groups of technologies, focusing on their basic ideas, how far along they are in their development, and what they could do. We will then look at how they fit into the global energy picture before ending with a study of their profitability compared to others using the key measure of Levelized Cost of Energy (LCOE).

The main renewable energy families are solar, wind, hydropower, biomass, and geothermal (plus marine energies). This chapter complements chapters 2 and 4 by focusing on the remaining sectors and a global comparison.

5.2 Synthetic Review of Major Renewable Sectors

5.2.1 Hydropower Energy

Hydropower is the oldest renewable electricity source and remains the world's leading renewable electricity producer. It uses the potential energy of water [1].

Large hydropower (plants with more than 10 MW). These plants are linked to huge reservoirs and can produce a lot of power and be dispatched quickly. They can change how much they make in a matter of minutes to meet demand, which is very important for keeping the grid balanced.

Small hydropower (PCH <10 MW)

They use small rivers and irrigation canals, and they often run-of-river, which is less harmful to the environment.

Pumped Energy Transfer Stations (STEP) in French: Station de Transfert d'Énergie par Pompage, equivalent to PSH)

True gravitational batteries, STEPs pump water to an upper reservoir during surplus electricity periods (off-peak hours, strong wind production) and turbine it during demand peaks. They constitute the most mature and efficient large-scale storage technology, with round-trip efficiencies of about 70–80% [2].

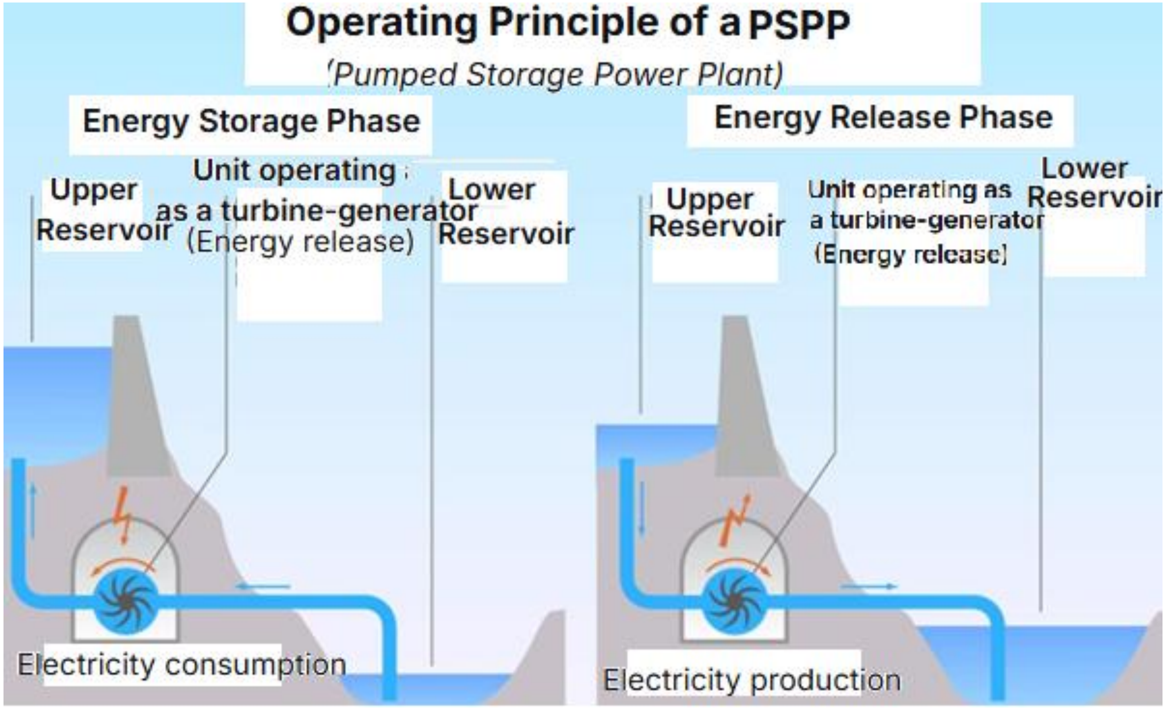

Fig. 5.1 - Operating principle of a Pumped Energy Transfer Station (STEP) with its two basins and reversible turbine-pump group [2]

5.2.2 Bioenergy

Bioenergy designates energy valorization of non-fossil organic matter called biomass. Its particularity is producing electricity, heat, and biofuels [3].

Electrical and Thermal Valorization

Electrical and thermal valorization of biomass means converting biomass into useful energy in the form of heat and/or electricity.

Methanization

Biogas, mostly methane (CH_4), is made when organic waste (like livestock waste and agri-food waste) breaks down without oxygen. We can burn this biogas in gas engines to make heat and electricity, or we can clean it up and turn it into biomethane to put into the natural gas grid.

Biofuels

1st Generation: From crops that are sugary, starchy, or oilseed (like corn, sugarcane, and rapeseed). People said it was bad because it was competing with food crops.

Second Generation: From non-food biomass that is lignocellulosic, like straw, wood, and agricultural waste.

3rd Generation: Based on microalgae culture, with much higher hectare yield.

Bioenergy considered carbon-neutral if resource sustainably managed (CO_2 emitted during combustion compensated by CO_2 absorbed by plants during growth) [3].

5.2.3 Geothermal Energy

Geothermal exploits Earth's internal heat. Average geothermal gradient: 3°C every 100m depth. Applications classified by resource temperature [4].

Low and Medium Energy Geothermal (30°C-150°C)

Direct heat use: urban heating, agricultural greenhouses, balneotherapy via geothermal heat pumps.

High Energy Geothermal (>150°C)

Electricity production: naturally present or produced steam (water injection in hot permeable rocks/reservoirs) drives turbine. Geographically constrained to high thermal gradient zones (rifts, volcanic arcs).

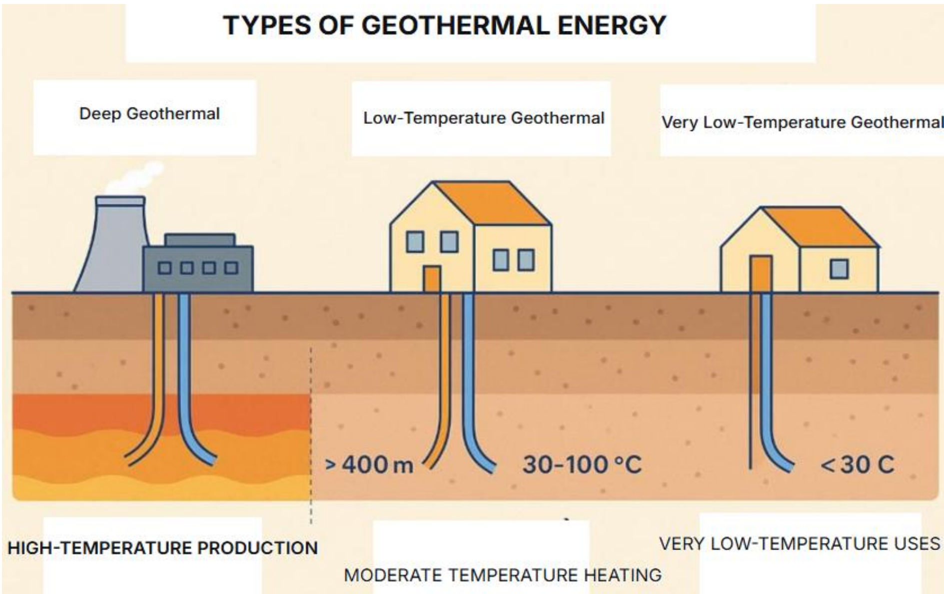

Fig. 5.2 - Diagram of different geothermal exploitation types, from low-energy heat pump to high-energy electricity plant [4]

5.2.4 Marine Energies (excluding hydrokinetic)

Ocean Thermal Energy (OTEC): Uses the difference in temperature between warm surface waters and cold deep waters.

Osmotic Energy: It takes advantage of the difference in saltiness between seawater and freshwater at the mouths of rivers.

5.3 A worldwide comparison of renewable energies

Solar and wind power are driving the rapid growth of renewables' share of the world's electricity mix, which increased from about 20% in 2010 to almost 30% in 2022 [1]. Distribution varies by region based on resources, policies, industrial context [1].

Table 5.1 - Approximate shares of main renewables in global electricity production 2022 and associated leaders [1].

Sector	Global Electricity Production Share	Leader Countries/Regions
Hydropower	15%	China, Brazil, Canada, USA
Wind	7.5%	China, USA, Germany, India
Solar PV	4.5%	China, USA, Japan, Germany
Bioenergy	2.5%	China, USA, Brazil, Germany
Geothermal	0.5%	USA, Indonesia, Philippines, Turkey

Country models:

Iceland: 100% renewable electricity (70% hydropower, 30% geothermal) [6].

Denmark: Wind pioneer (>50% consumption 2022, aiming for 100% by 2030) [7].

Costa Rica gets almost all of its electricity from renewable sources, including hydropower, geothermal, and wind.

Algeria mix dominated by natural gas. PNEREE challenge: replicate leaders' diversification, prioritizing solar then wind/biomass.

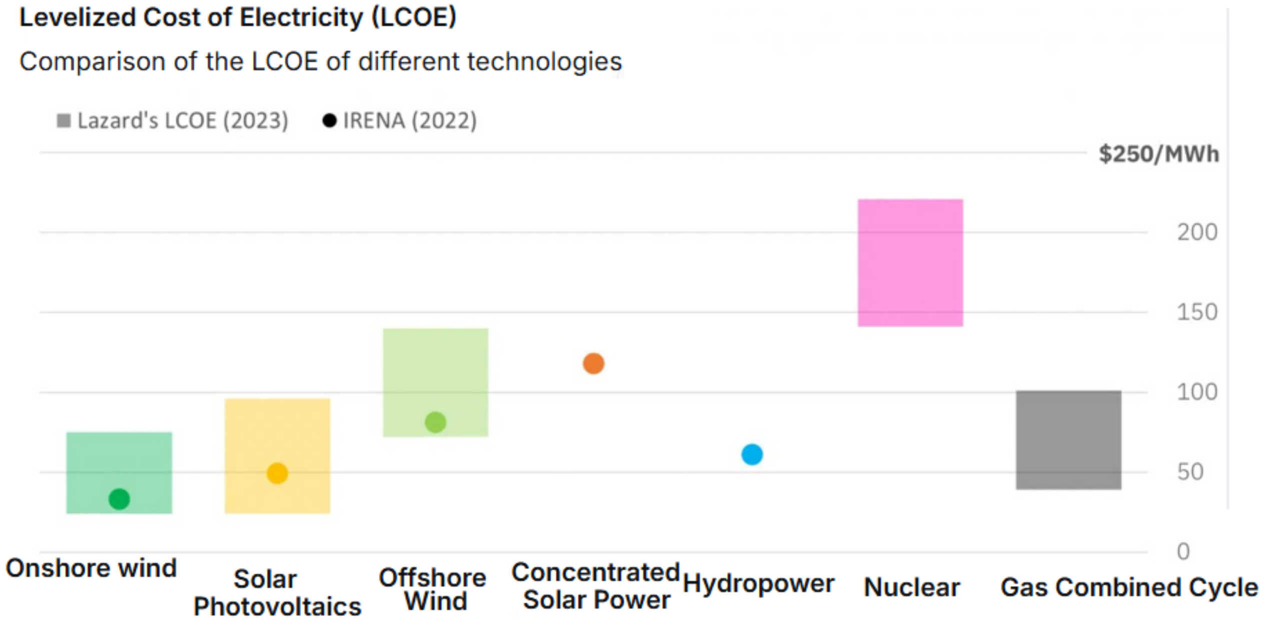

Fig. 5.3 - Evolution of renewable share in global electricity production 2010-2022, showing solar/wind exponential growth [1]

5.4 Profitability Analysis - Levelized Cost of Energy (LCOE)

Economic profitability decisive for renewable deployment. Universal comparison indicator: Levelized Cost of Energy (LCOE) [8].

5.4.1 LCOE Definition and Calculation

LCOE represents total discounted construction/operation cost of electricity plant over lifetime, divided by total discounted expected electricity production:

$$LCOE = \frac{\text{Investment} + \text{Operation} + \text{Fuel}}{\sum_t \frac{\text{Production}}{(1+r)^t}} \tag{5.1}$$

LCOE integrates:

CAPEX (Capital Expenditures): Equipment purchase, construction, installation.

OPEX (Operational Expenditure): Staff, maintenance, and insurance.

Cost of fuel: none for solar and wind, but high for biomass and geothermal.

Capacity Factor: Actual vs. full-power annual production ratio. Key parameter.

5.4.2 Renewable LCOE Comparison

IRENA (International Renewable Energy Agency) data show spectacular solar/wind LCOE drop, making them subsidy-free competitive.

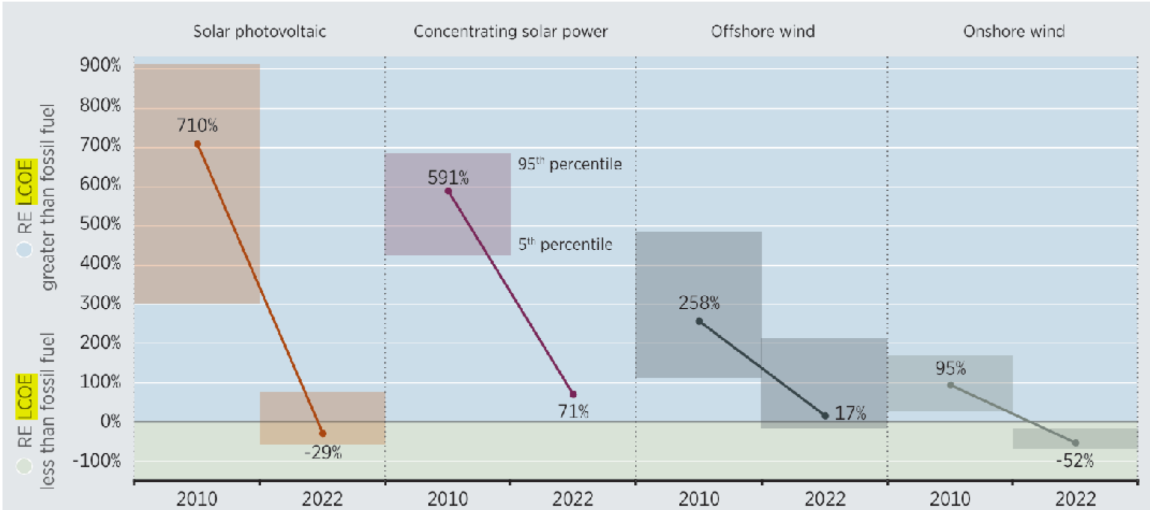

Fig. 5.4 - Evolution of global average LCOE for main renewable technologies 2010-2022 (solar PV/onshore wind sharp reduction) [8]

-Recent data analysis (2022) [8]:

Solar PV utility-scale: Lowest LCOE (30-80 $/MWh). Cheapest option in many regions.

Onshore Wind: Very competitive (25-70 $/MWh).

Geothermal: High LCOE (60-150 $/MWh) due to drilling/exploration risks.

Hydropower: Wide range (20-200 $/MWh) depending on plant size and site complexity.

Bioenergy: Variable (50-150 $/MWh), biomass cost dependent.

LCOE factors: local resource, financing costs, scale economies, technological maturity.

5.4.3 Profitability and System Value

LCOE is a cost metric, not a profitability metric: profitability depends on tariff structure, self-consumption rate, financing conditions, policy incentives, and the system value of dispatchability/ancillary services.

5.5 Conclusion

This chapter concludes our electricity production devices overview. We surveyed remarkably rich/diverse technological landscape from fundamentals to advanced technologies [9-11].

Common Challenges Synthesis:

Intermittency: Solved by hybridization/storage.

Grid Integration: Requires smart grids.

Costs/Financing: LCOE falling but CAPEX barrier.

Social/Environmental Acceptability: Crucial for all projects.

Algeria Perspective: Exceptional sunshine, wind potential, biomass resources. Resolute PNEREE implementation + local industry/skills development reduces gas dependence for domestic electricity, frees gas volumes for export/petrochemistry, contributes climate fight [12-14].

In conclusion, energy future not single winner but diversified, resilient, intelligent mix where each renewable finds place per comparative advantages/local specificities. Complementarity key to sustainable/reliable energy system.

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CHAPTER 5 : KEY POINTS TO RETAIN

Energy transition relies on diversified mix, not miracle technology.

Four major renewable families detailed: Hydropower, Biomass, Geothermal, Marine energies.

Hydropower world's #1 renewable electricity: Large dispatchable, Small low-impact, STEP mature mass storage (70-80%).

Biomass only dispatchable renewable with heat+electricity: Combustion cogeneration, Methanization biogas, Biofuels.

Geothermal 24/7 availability, very low CO_2 footprint, long lifespan.

Marine energies immense potential, emerging: Currents/waves/tides high density but technical challenges.

LCOE analysis: Key indicator comparing sectors.

REVIEW POINTS

Hydropower only dams? STEPs essential for electricity storage.

Biomass is often perceived as “dirty”, but if the resource is sustainably managed, its carbon balance can be considered close to neutral.

Geothermal is not limited to volcanic areas; sedimentary basins also enable low- and medium-temperature geothermal applications.

Marine energies mature? Tides predictable but high costs/corrosion.

LCOE total real cost? Chapter specifies system value equally important.

SELF-ASSESSMENT

QUESTION 1. Why is diversified mix indispensable?

SOLUTION: Because no technology satisfies simultaneously dispatchability, low cost, low impact, universal availability. Mix combines each sector’s advantages.

QUESTION 2. Major large hydropower advantage?

SOLUTION: Dispatchability - adjusts power rapidly for grid stabilization.

QUESTION 3. Why STEPs important?

SOLUTION: Gravitational batteries storing electricity large-scale (70-80% efficiency).

QUESTION 4. **Biomass particularity?**

SOLUTION: Dispatchable renewable producing heat, electricity, biofuels.

QUESTION 5. Key geothermal distinguishing asset?

SOLUTION: Continuous 24/7 production independent of climate/seasons.

QUESTION 6. Why marine energies promising but limited today?

SOLUTION: Very high energy density but limited by costs, corrosion, offshore installation difficulty.

QUESTION 7. What does LCOE represent?

SOLUTION: Discounted kWh production cost enabling objective sector comparison.

MULTIPLE CHOICE QUESTIONS

QUESTION 1: Which sector world's leading renewable electricity source?

A. Solar

B. Wind

C. Hydropower

D. Geothermal

SOLUTION: C. Hydropower

QUESTION 2: STEP is:

A. Thermal production

B. Mass storage technology

C. Biofuel type

D. Submarine turbine

SOLUTION: B. Mass storage technology

QUESTION 3: Biomass enables:

A. Electricity only

B. Heat+ electricity+ fuels

C. Green gas only

D. Nuclear energy

SOLUTION: B. Heat+ electricity+ fuels

QUESTION 4: Geothermal production:

A. Intermittent

B. Random

C. Continuous

D. Wind-dependent

SOLUTION: C. Continuous

QUESTION 5: Tidal energy:

A. Unpredictable

B. Very predictable

C. Fossil technology

D. Storage technology

SOLUTION: B. Very predictable

QUESTION 6: LCOE serves:

A. Fluid pressure

B. Compare sector costs

C. Turbine power

D. STEP sizing

SOLUTION: B. Compare sector costs

QUESTION 7: Common renewables challenge:

A. Radioactivity

B. Intermittency

C. Turbine shortage

D. Wind scarcity

SOLUTION: B. Intermittency

GENERAL CONCLUSION

The analytical path undertaken in these course notes, from fundamental electromagnetism to the most advanced renewable energy conversion technolog leads to an unequivocal conclusion: the energy transition is not only necessary and urgent, but also technologically mature and economically viable. The five chapters of this work, linked in a logical and cumulative manner, have made it possible to establish a complete and detailed mapping of the new energy landscape.

Chapters 2, 4, and 5 have shown, with concrete data, the economic competitiveness achieved by solar photovoltaic and onshore wind power. Their rapidly declining LCOE now makes them among the least expensive generation options in many regions worldwide, overturning the old prejudice that “green” necessarily means “expensive”. Algeria, with its exceptional solar resource and significant wind potential, therefore holds a decisive comparative advantage for its future development.

However, this course notes also highlighted the fundamental challenge of this new era: intermittency. The variability of sunshine and wind—even if predictable in the short term—requires a profound redesign of electrical systems. Chapters 3 and 5 identified solutions to this difficult issue. Intelligent hybridization of sources, combined with diversified storage solutions—from lithium-ion batteries for the short term to pumped storage (STEP) and the hydrogen pathway for the long term—emerges as the cornerstone of a stable grid. The system value of dispatchable energy sources, such as hydropower and biomass, has been reaffirmed as an indispensable complement.

The technologies explored—from predictable tidal-stream power to high-efficiency tandem photovoltaic cells—are not in competition but in complementarity. Each provides a specific response to a particular need, depending on the geographic, climatic, and economic context. The future lies not in a single winner, but in a diversified and optimized energy mix, in which the robustness of national grids will be reinforced by the agility of microgrids and decentralized generation systems.

For Algeria, the results of this analysis are strategic. The success of the National Program for Renewable Energies and Energy Efficiency (PNEREE) will not be limited to installing additional gigawatts. It will necessarily require: (1) developing an industrial sector and local skills in engineering, maintenance, and grid management; (2) modernizing and adapting the national electricity grid to make it more flexible, intelligent, and capable of absorbing decentralized and variable generation; and (3) establishing incentive financing and regulatory mechanisms to stimulate private investment and self-consumption.

From a geopolitical standpoint, this transition offers Algeria a historic opportunity to reshape its position. By reducing domestic consumption of natural gas for electricity generation, Algeria could free substantial volumes for higher value-added uses (petrochemicals) or for export, thereby transforming its gas rent into a lever for sustainable economic development.

Ultimately, this work has shown that the QUESTION is no longer whether the energy transition will take place, but how—and at what pace—it will be implemented. Technological and economic barriers have largely been removed. The remaining challenges—grid integration, storage, and social acceptance—are now mainly issues of systems engineering, governance, and political will.

Electricity generation, once a purely industrial human activity, is now being reinvented as a symbiosis between cutting-edge technology and the natural forces of our planet. It is ceasing to be part of the problem and becoming an integral part of the environmental and economic solution. Future generations may well regard the fossil-fuel era as an early phase in energy history, compared with the diversified low-carbon systems being deployed today. These course notes therefore conclude on a note of reasoned optimism. The technological arsenal needed to build a clean, secure, and prosperous energy future is at our disposal. Science has delivered on its promises. It is now up to decision-makers, industry, and citizens to write—together—the next chapter of this great human adventure.

The integration of hybrid renewable energy systems constitutes a major strategic lever for the global energy transition, as highlighted by leading international and national institutions. The International Energy Agency emphasizes in its World Energy Outlook 2025 that hybrid systems combining wind, solar, and storage represent the most promising pathway to achieving carbon neutrality by 2050, with a projected 65% increase in installed hybrid capacity by 2030 [1]. From a technical standpoint, the analysis of structural dynamics in the renewable energy economy by [2] reveals that hybrid approaches strengthen the resilience of power grids against demand fluctuations, notably through longitudinal input-output models that quantify the sectoral interdependencies induced by this transition [2]. Furthermore, the study by [3] on co-firing municipal sludge coupled with power generation demonstrates that energy balance and thermo-economic analysis are essential for optimizing the overall performance of hybrid installations, with a potential reduction in carbon emissions of approximately 30% compared to conventional systems [3]. In the African context, authors in [4] identify the emerging opportunities of renewable energy entrepreneurship in Sub-Saharan Africa, highlighting that hybrid systems offer particularly attractive economic prospects in rural areas where high wind power density and solar irradiance enable optimal seasonal complementarity [4]. At the national level, the Centre de Développement des Énergies Renouvelables (CDER, 2024) and the Haut-Commissariat aux Énergies Renouvelables et à l'Efficacité Énergétique [5] converge on the necessity of integrating local renewable resources solar in Algeria within hybrid energy systems tailored to the climatic and structural specificities of each country [5, 6]. Finally, the analysis by [7] on hybrid system selection in Algeria, based on a scenario-based weighting approach and Monte Carlo sensitivity, confirms that decision-making robustness crucially depends on accounting for uncertainties related to renewable resources and investment costs, an issue that the [8] broadens to the global scale in its State of Energy Policy 2026 by calling for adapted regulatory frameworks to accelerate the deployment of these integrated systems [7, 8].

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APPENDIX 1
METHODOLOGY FOR SIZING AN AUTONOMOUS PHOTOVOLTAIC SYSTEM

1 Objective

Provide a rigorous method for sizing a stand-alone PV system intended to power a specific load, integrating losses, safety factors, and electrical constraints.

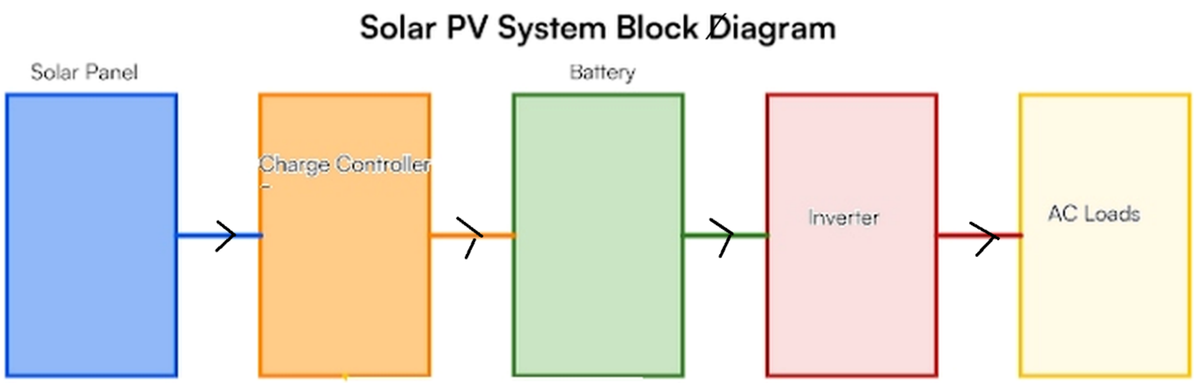

Fig. 1: Standalone Solar PV System Architecture: From DC Generation to AC Load Supply

This simple example illustrates how it works:

- The PV generator powers a charge controller, which charges the battery. The stored energy is then converted to AC by the inverter and finally supplied to the AC load.

2 Sizing steps

1. Assessment of daily workload

The first step is to estimate daily energy consumption:

$$E_{load} = \sum_i P_i \times t_i \quad [Wh/j]$$

- Pi: power of device [W]
- ti: Device usage time [h/d]

Example :
A small house consumes:

Device	Power (W)	Time (h/day)	Energy (Wh/day)
LED lights	50	6	300
Fridge	100	24	2400
Total	**150**	-	**2700**

Table 1: Daily Energy Consumption Profile: Load Assessment for Solar PV System Sizing

Eload=2700 Wh/day

2. Correction of losses and autonomy

To take into account:

- Controller efficiency ηc
- Inverter efficiency ηinv
- Maximum discharge depth DOD

$$E_{corrected} = \frac{E_{load}}{\eta_c \cdot \eta_{inv}} \quad [Wh/j]$$

3. Sizing of the photovoltaic generator

Daily energy available per PV module:

$$E_{PV} = P_{STC} \times H_{eff} \times \text{Loss factor}$$

- P_{STC}: nominal power of the module [W]
- H_{eff}: effective daily irradiation [h]
- Loss factor: temperature, dust, wiring (≈0.75–0.85)

Number of modules required:

$$N_{modules} = \frac{E_{corrected}}{E_{PV}}$$

4. Battery sizing

Cbat : Required capacity:

$$C_{bat} = \frac{E_{corrected} \times N_j}{V_{bat} \times DOD} \quad [Ah]$$

- Nj desired number of days of battery life
- Vbat: system voltage [V]
- DOD: maximum discharge depth (%)

Numerical example:

$$C_{bat} = \frac{2700 \times 2}{48 \times 0.8} \approx 140.6 \text{ Ah}$$

5. Selection of the regulator and inverter

- **Regulator**: select the maximum charging current
  $(I_{max} = \frac{P_{PV,total}}{V_{bat}})$
-
- **Inverter**: nominal power ≥ maximum simultaneous load power

6. Complete Example

Data :

- House: 2.7 kWh/day
- PV: 300 Wp module, 5 h/day irradiation, loss factor 0.8
- Battery: 48V, 2-day battery life, 80% DOD
- Example UNISUN 300.12 M for PV module

PV calculation:

$$E_{PV} = 300 \times 5 \times 0.8 = 1200 \text{ Wh/module/j}$$

$$N_{modules} = \frac{2700}{1200} \approx 3 \text{ modules}$$

Battery calculation:

$$C_{bat} = \frac{2700 \times 2}{48 \times 0.8} \approx 141 \text{ Ah}$$

APPENDIX 2

Table of Energy Sources Comparison [1-5]

Source	Maturity	Dispatchability	Typical Capacity Factor	Relative Cost / LCOE	Local Constraints
Photovoltaic	Very high	Low	15–25%	Continuously decreasing	Heat, dust, cleaning
Onshore wind	High	Medium	20–40%	Competitive	Wind variability, site-dependent
Natural gas	Very high	Excellent	>60%	Moderate cost but CO_2 emissions	Fuel dependency
Hydroelectric / PSP	High	Excellent	Variable	High investment, low long-term cost	Limited water resource
Biomass	Medium	Medium	40–60%	Variable	Dispersed resource, logistics
CSP	Medium	Medium with storage	25–45%	High CAPEX	Water needs, maintenance

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APPENDIX 3

1. Solar Potential of Algeria

1.6.1 Solar Resource and Priority Areas

Algeria has the highest solar potential in the MENA region, with average annual global horizontal irradiation exceeding 2,200 kWh/m² in the Sahara and 1,900 kWh/m² in the High Plateaus . This potential, combined with a vast and sparsely populated territory, positions Algeria as a strategic player in the African and Mediterranean energy transition [1-6].

The Algerian territory is divided into three distinct solar zones :

Saharan zone (South): Irradiation > 2,200 kWh/m²/year, with more than 3,000 sunshine hours per year. The wilayas of Adrar, Ouargla, Biskra, and Tamanrasset concentrate the best potential. This zone accounts for more than 70% of the planned renewable capacity.

High Plateaus zone: Irradiation of 1,900 to 2,000 kWh/m²/year. The potential is complemented by wind resources (winds of 7.5 m/s at 100 m height along the coast) .

Northern zone (coastline): Lower irradiation (~1,600 kWh/m²/year) but close to consumption centers. It is favored for distributed solar and hybrid projects.

The technically and economically exploitable solar energy in Algeria is estimated at about 170 TWh/year, which is several times the country's current electricity consumption.

1.6.2 National Energy Context

In 2024, Algerian electricity production relied on natural gas for 99%, while solar contributed only about 1%. National electricity consumption is growing by 4 to 5% per year, driven by demographic growth and industrialization. This near-total dependence on hydrocarbons exposes the economy to gas price fluctuations and reduces the volumes available for export, depriving the country of substantial revenues .

The national strategy aims to increase the share of renewable energy to 27% of electricity production by 2035 , with an intermediate target of 15 GW of solar capacity. This ambition is part of a broader vision of economic diversification and the preservation of natural gas resources for high-value export markets.

1.6.3 Solar Programs and Projects in Algeria

Algeria has structured its solar deployment around ambitious national programs, coordinated by the Ministry of Energy and Renewable Energies through Sonelgaz and the Algerian Energy Company (AEC) .

The 15 GW national program

The national program, launched in 2021, aims to install 15 GW of PV solar capacity by 2035. It is divided into several phases :

Phase 1 (2023–2026): 3.2 GW distributed across 22 plants ranging from 80 to 220 MW in 12 wilayas in the South and the High Plateaus. The overall progress of this phase reached 40% in April 2026 .

Phase 2 (2026–2030): An additional 6.8 GW, with greater openness to public-private partnerships and foreign investment.

Phase 3 (2030–2035): 5 GW to reach the total target of 15 GW.

The "Solar 1,000 MW" program is the annual operational component, aiming to install 1 GW of new capacity each year starting in 2026 . In 2025, solar panel imports were multiplied by six, increasing from 0.35 GW to 2.1 GW, signaling the country's concrete commitment .

Ongoing and recent flagship projects

Several major projects illustrate the practical implementation of Algeria's strategy. Table 1 summarizes innovative energy proposals adapted to Algeria's specific conditions and their comparative benefits.

Table 1: Innovative energy proposals adapted to Algeria's specific conditions and their comparative benefits.

Project	Location	Capacity (MW)	Status	Specific Features
Tendla	El Meghaier	200	Commissioned (04/2026)	Phase 1 of the 3.2 GW program
El Ghrous	Biskra	200	Commissioned (04/2026)	Phase 1 of the 3.2 GW program
Hassi Delaa	Laghouat	300 AC / 362 DC	Under construction (2024–2026)	Largest plant in Algeria, bifacial modules
Guerrara	Ghardaïa	82	Under construction	Associated with Hassi Delaa
Ouled Djellal	Biskra	80	Planned for 2025	2 GW program (2023)

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APPENDIX 4

PERSPECTIVES AND ORIGINAL CONTRIBUTIONS

3.1 Proposals Specific to Algeria

Algeria stands at a critical juncture in its energy transition trajectory. As the largest country in Africa and a historical hydrocarbon exporter, the nation faces the dual challenge of decarbonizing its domestic electricity sector—currently dominated by natural gas—and repositioning itself within the emerging global green economy [4]. With over 2,000 hours of annual sunshine and DNI levels exceeding 2,200 kWh/m² in the Sahara, Algeria possesses among the world's most favorable conditions for solar energy development [2]. However, the effective harnessing of this potential requires moving beyond conventional technology deployment toward context-specific innovations that address the country's unique geographical, climatic, and infrastructural constraints [1-16].

The following proposals emerge from a systematic analysis of Algeria's renewable resource endowment, grid infrastructure limitations, and socio-economic priorities. Each innovation is designed to exploit a distinct comparative advantage—whether the exceptional solar irradiance of the southern provinces, the abandoned mining infrastructure of the northern highlands, or the saline wastelands that cover significant portions of the national territory. These proposals are not merely technology transfers; they represent integrated systems tailored to Algerian conditions, with explicit consideration for water scarcity, grid stability requirements, and the imperative of economic diversification beyond fossil fuel dependence [3][4].

The originality of these contributions lies in their systemic coupling of multiple energy vectors and land uses. Rather than treating solar, wind, hydrogen, storage, and agriculture as separate domains, each proposal explores synergistic configurations that enhance overall system efficiency and economic viability. This approach reflects a fundamental shift from single-technology optimization toward integrated energy system design—a paradigm increasingly recognized as essential for achieving deep decarbonization in resource-constrained environments [1].

To address Algeria's unique energy challenges, several innovative solutions have been proposed. Table 1 describes these initiatives and compares their respective advantages in terms of technical feasibility, economic viability, and grid integration potential.

Table 1. Innovative Energy Proposals Specific to Algeria: Description and Comparative Advantages

Innovation	Description	Comparative Advantage
Agrivoltaic PV	Electricity-agriculture cogeneration in desert zones	Double valorization, fight against desertification
Hybrid CSP	CSP-PV coupling with shared thermal storage	DNI optimization, increased dispatchability
Solar H_2	High-temperature electrolysis via CSP	Electrolysis efficiency >30%
Underground PSP	Pumped-turbine storage in abandoned mines	No dam, low environmental impact
Halophyte biomass	Salicornia cultivation for biogas in saline zones	Does not compete with food agriculture

1. CSP with Thermal Storage

Table 2 collects recent CSP plant data with thermal storage, enabling techno-economic comparison for hybrid system sizing.

Table 2. CSP with Thermal Storage: Recent Technical and Economic Data

Aspect	Recent Data
Global CSP LCOE 2024	USD 0.092/kWh (77% decrease since 2010)
Hybrid CSP-PV in Algeria	Optimized LCOE of 7.19 EUR/kWh for CP3 configuration (solar tower + PV) with 9h storage
Thermal storage	For storage >4h, CSP more competitive than PV+batteries

CSP with integrated thermal energy storage (TES) represents a key solution for dispatchable renewable electricity in Algeria. The global weighted-average LCOE for CSP reached USD 0.092/kWh in 2024, with a 77% reduction since 2010, driven by longer storage durations and improved capacity utilization in high-DNI regions [1]. For storage durations exceeding four hours, CSP with TES can be more competitive than PV combined with batteries [1].

Original Proposal for Algeria: Development of hybrid CSP-PV plants with shared thermal storage in high-DNI zones (Adrar, Tamanrasset), exploiting the Sahara's solar potential with increased dispatchability. Techno-economic modeling for Algeria shows that a central receiver tower with molten salt storage and backup achieves an optimal capacity factor of 87% and LCOE of 15.11 Cent/kWh [2]. IRENA's North Africa planning scenarios project 75 GW of CSP capacity by 2040 in the Transition scenario, with Algeria representing more than 80% of the region's CSP installed capacity [3].

2. Green Hydrogen

Table 3. Green Hydrogen: Recent Strategic and Project Data

Aspect	Recent Data
Algerian national strategy	2.5 GW of PEM electrolyzers by 2040, production of 1.2 Mt/year of green H_2
South H_2 Corridor	MoU signed in October 2024 between Sonatrach/Sonelgaz and VNG (Germany), Snam (Italy), VERBUND (Austria) for export to Europe
HySolThane Project	Enrichment of natural gas with hydrogen for buses in Algiers

Algeria's national hydrogen strategy targets 2.5 GW of electrolyzer capacity by 2040, with production of 1.2 Mt/year of green hydrogen [4]. The South H2 corridor MoU was signed in October 2024 between Sonatrach/Sonelgaz and European partners (VNG, Snam, VERBUND) for export to Europe [4]. High-temperature electrolysis via CSP using solid oxide electrolysis cells (SOEC) can achieve efficiencies exceeding 30% [5].

Original Proposal: High-temperature electrolysis via CSP (SOEC technology) to achieve efficiencies >30%, coupling hydrogen production and thermal storage in Algerian desert zones. This approach leverages the country's high DNI (1700-2200 kWh/m²/year) and existing natural gas infrastructure for hydrogen export [4].

3. Smart Grids

Table 4. Smart Grids: Recent Infrastructure and Market Data

Aspect	Recent Data
SCADA Modernization	Sonelgaz launches SCADA system rehabilitation in 2026, investment of 60 billion USD over 2024-2029
Sonelgaz-Siemens MoU	Collaboration for renewable energy and green hydrogen
Global SCADA Market	2.58 billion USD (2025) → 4.91 billion USD (2034)

Algeria is advancing a comprehensive overhaul of its national electricity grid centered on a new-generation SCADA system, with full deployment anticipated by 2026 [6]. The power SCADA market is projected to expand from USD 2.58 billion in 2025 to USD 4.91 billion by 2034 [6]. Sonelgaz and Siemens signed an MoU in 2025 focusing on renewable energy and green hydrogen development [6]. The GEAT joint venture (Sonelgaz-GE Vernova) is expanding into high-voltage substations and grid automation equipment to enable renewable energy integration [7].

Original Proposal: Integration of a predictive AI-based management system for solar and wind production forecasting, reducing reserve costs and improving grid stability. This aligns with Algeria's 15 GW renewable target by 2035 and the SCADA modernization program [6].

4. PSP in Arid Sites

Table 5. Underground PSP in Arid Sites: Technical Characteristics and Algerian Potential

Aspect	Recent Data
Underground PSP	Use of abandoned mines for pumped-turbine storage (UPSH)
Advantages	No dam required, low environmental impact, reuse of existing infrastructure
Potential in Algeria	Former coal mines and disused mining deposits in the North (Ouenza, Djebel Onk)

Underground pumped storage hydroelectricity (UPHS) addresses energy storage challenges by using buried reservoirs, particularly in abandoned mines or depleted formations [8]. Estonia's 500 MW Zero Terrain underground PHS project demonstrates the feasibility of this technology, with construction beginning in Q2 2025 [9]. In arid regions, underground PSP avoids evaporation losses and eliminates the need for surface dams [8].

Original Proposal: Feasibility study for underground PSP in abandoned mines of northern Algeria (Ouenza, Djebel Onk), coupled with PV for pumping, offering a storage solution without dams and without evaporation in arid climate. This approach reuses existing mining infrastructure while minimizing environmental impact [8].

5. Agrivoltaic and Halophyte Biomass

Table 6. Agrivoltaic and Halophyte Biomass: Recent Scientific and Technical Data

Recent Data
Exponential growth of scientific publications since 2020, *Applied Energy* journal leader (11%)
Positive impact on vegetation and rainfall (albedo effect)
Salicornia spp. for biogas in saline zones, yield 300-500 m³ biogas/t DM

Agrivoltaic systems have experienced exponential growth in scientific publications since 2020, with *Applied Energy* as the leading journal (11% of publications) [10]. Solar development in deserts can positively impact vegetation and rainfall through albedo effects [11]. Halophyte biomass (Salicornia spp.) can produce 300-500 m³ biogas per ton of dry matter in saline zones without competing with food agriculture [12].

Original Proposal: Development of agrivoltaic pilot zones in the northern Sahara (Ghardaïa, Ouargla) with salicornia cultivation under PV panels, simultaneously producing electricity, biofuels, and combating desertification. This dual-use approach maximizes land productivity in arid regions while addressing food-energy-water nexus challenges [10-16].

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APPENDIX 5

Architecture and Integration of Intelligent Energy Systems

5.1. Architecture of an Intelligent Electrical Grid (Smart Grid)

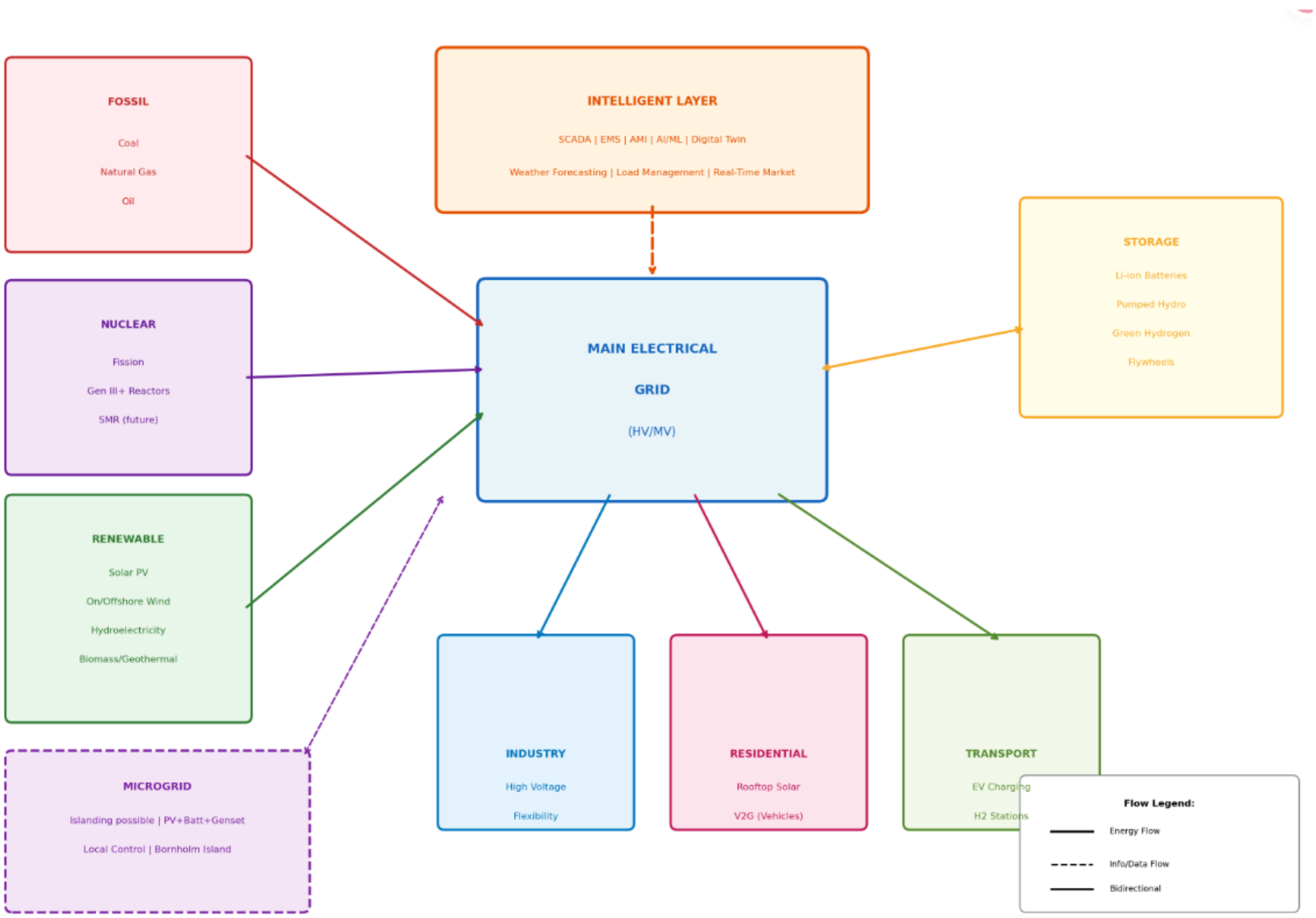

Fig. 1: Smart Grid Architecture

This diagram illustrates the complete architecture of a modern Smart Grid, showing:

- The **3 generation sources** (fossil, nuclear, renewable) connected to the main grid
- The **intelligent layer** (SCADA, EMS, AI/ML, Digital Twin) that supervises the system
- **Storage systems** (batteries, pumped hydro, hydrogen) in bidirectional interaction
- **Active consumers** (industry, residential, transport) with V2G and self-consumption
- The **microgrid** in islanding mode (e.g., Bornholm Island)

5.2. Comparative Table of Energy Sources in 2025

Table 1: Comparative Energy Sources Table

Source	LCOE (USD/MWh)	CapEx (USD/kW)	Lifetime (years)	Capacity Factor (%)	CO_2 (kg/MWh)	Dispatchability	Technology Maturity
Solar PV (utility)	35–65	800–1,200	25–30	20–35	35	Low (intermittent)	Very mature
Wind (onshore)	40–80	1,200–1,800	25–30	25–45	15	Low (intermittent)	Very mature
Wind (offshore)	85–140	3,000–5,000	25–30	35–50	15	Low (intermittent)	Mature
Natural Gas (CCGT)	66–130	800–1,200	30–40	50–93	450	High (dispatchable)	Very mature
Coal	90–171	2,000–3,500	40–50	40–85	900	High (dispatchable)	Very mature
Nuclear	80–160	4,000–8,000	50–60	85–93	10	Very high (base load)	Very mature
Hydroelectric	40–80	2,000–5,000	50–100	30–60	24	High (dispatchable)	Very mature
Solar + 4h Storage	85–105	1,500–2,500	20–25	20–30	40	Medium	Developing
Green Hydrogen	120–200	2,500–4,000	20–25	30–50	0	High (long-term)	Emerging

Renewable | Fossil | Nuclear | Hybrid | Emerging

Table 2: Classical Grid vs. Smart Grid: Comparative Architecture and Operational Features

Criterion	Leader	Observation
Lowest LCOE	Solar PV (35–65 $/MWh)	Cheaper than coal
Lowest CO_2	Nuclear (10 kg/MWh)	Followed by wind (15)
Dispatchability	Nuclear / Gas	Intermittent renewables require storage
Maturity	All except H_2 green	Solar + storage under development

5.3. Comparison: Classical Grid vs. Smart Grid

Comparative analysis:

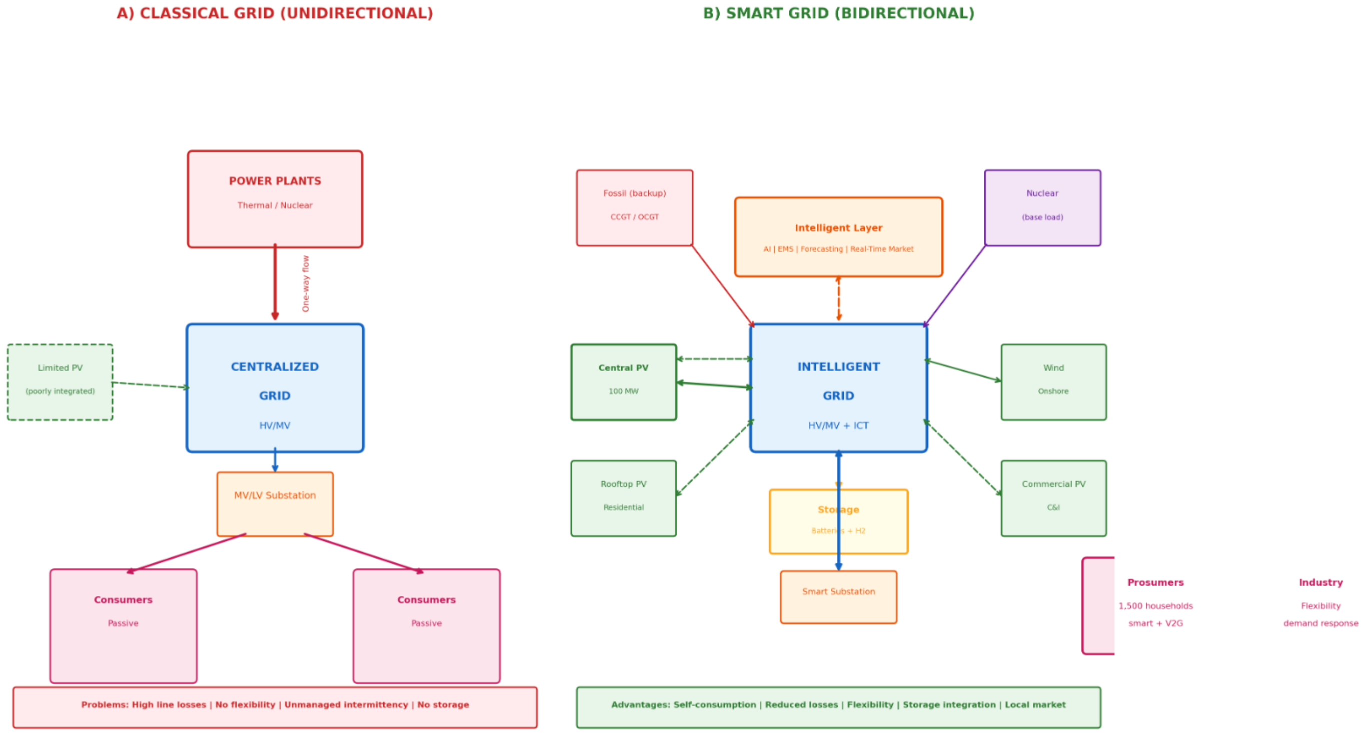

Fig. 2 : Classical Grid vs Smart Grid

Table 3: Classical Grid vs. Smart Grid: Comparative Overview of Key Technical and Operational Aspects

Aspect	Classical Grid	Smart Grid
Flow direction	Unidirectional (central → consumer)	Bidirectional (prosumers)
Generation	Centralized (thermal/nuclear)	Distributed (PV, wind, biomass)
Consumers	Passive	Active (prosumers with V2G)
Storage	Absent	Batteries + H_2 + V2G
Control	Manual / Basic SCADA	AI + EMS + Digital Twin
Losses	High (8–12%)	Reduced (−8% observed in Bornholm)

5.4. Case Study: Solar Integration in the Algerian Grid (Sonelgaz)

Context: Algeria targets **15 GW of renewable energy by 2035** with a current mix of approximately **97% natural gas**

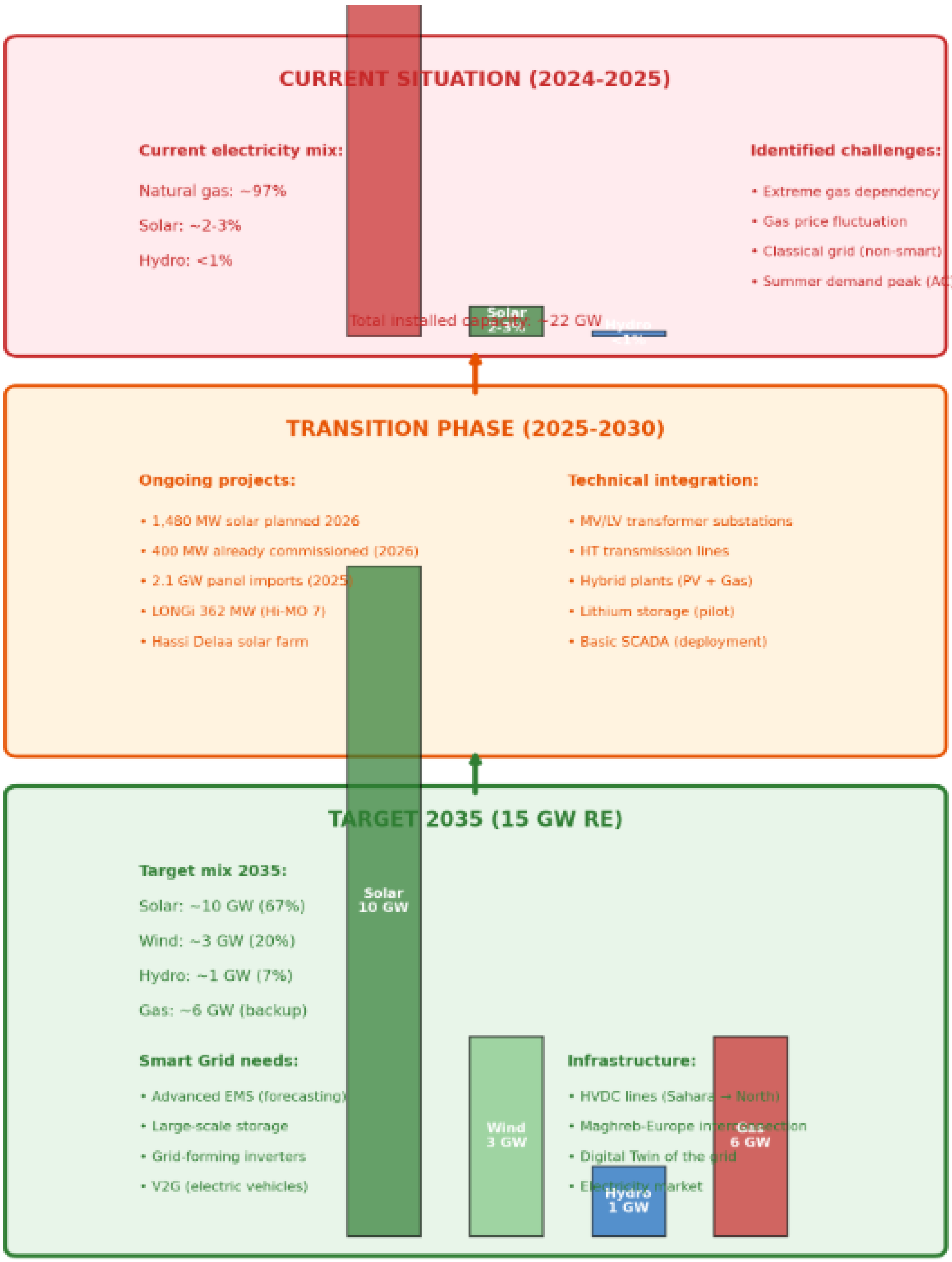

Fig 3: Algeria 2035 Renewable Energy Transition Roadmap

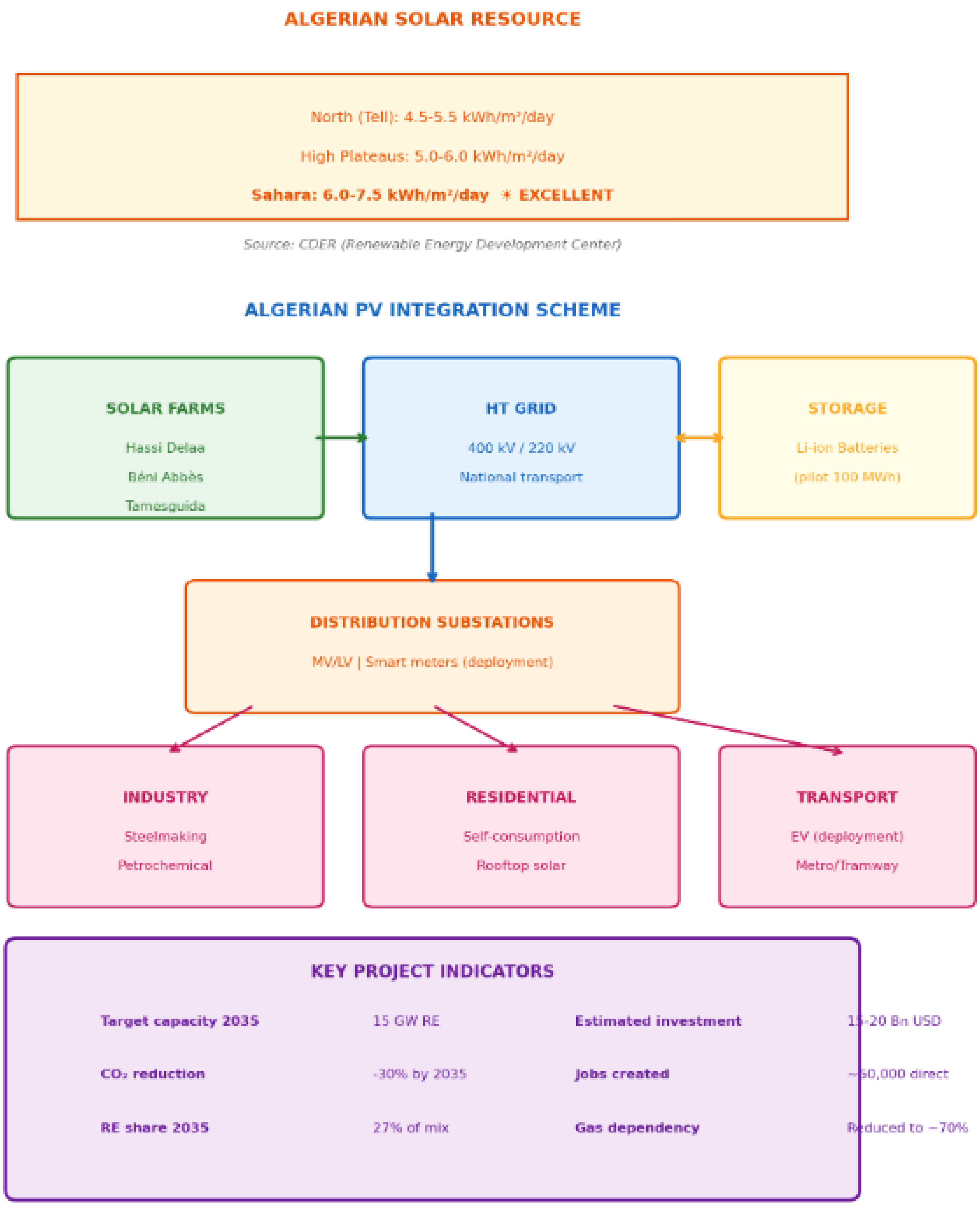

Fig 4: Algeria Case Study

Transition phases**:**

1. Current situation (2024–2025)**: 22 GW total, ~97% gas, classical grid**
2. Transition (2025–2030)**:** 1,480 MW solar planned, 2.1 GW panel imports, LONGi 362 MW projects
3. Target 2035: 15 GW RE (10 GW solar, 3 GW wind, 1 GW hydro)

Specific challenges**:**

- Summer demand peak (air conditioning) coinciding with solar peak

- Non-smart grid requiring urgent modernization
- Need for HVDC lines Sahara → North and Maghreb-Europe interconnection

5.5. Case Study: Bornholm Microgrid (Denmark) — EcoGrid 2.0

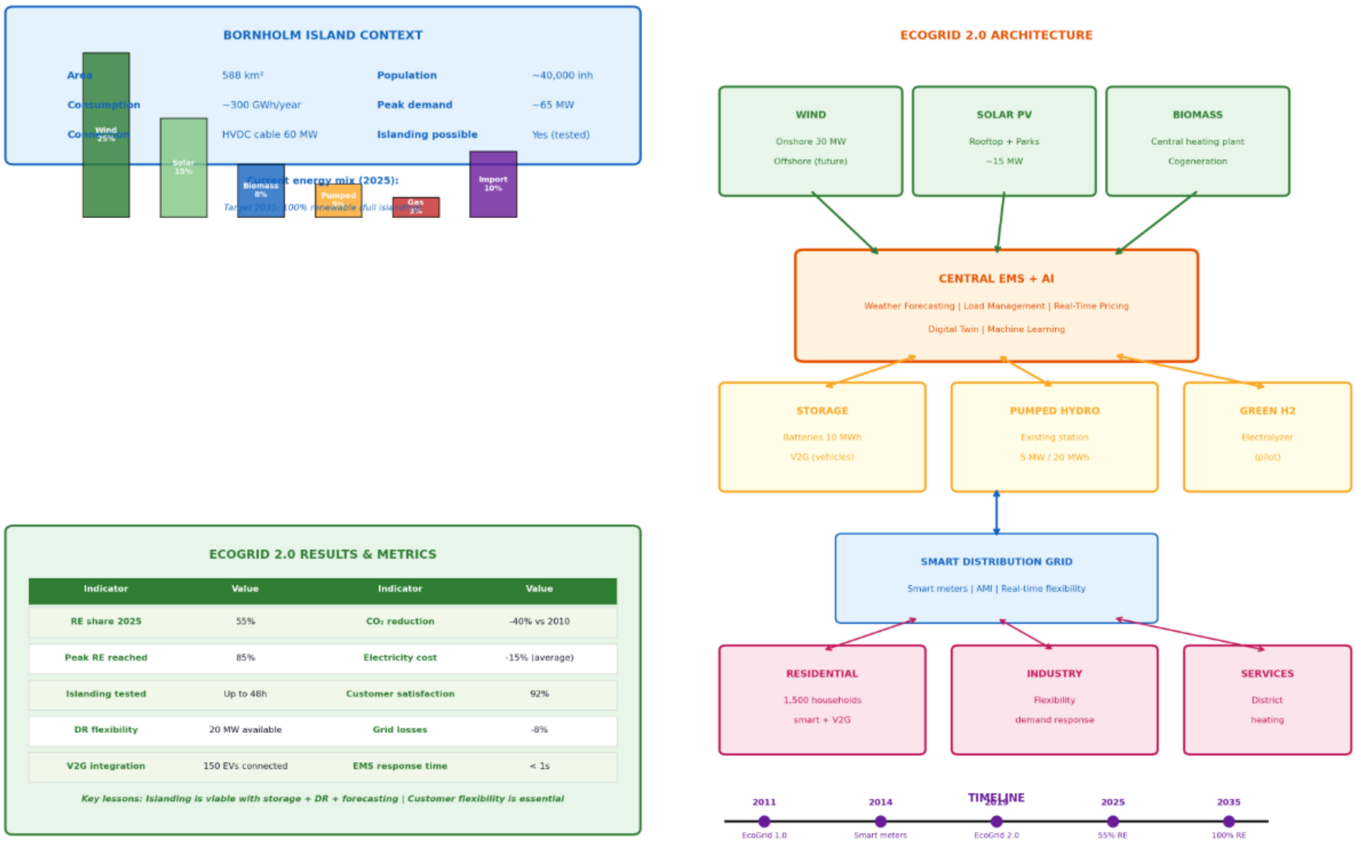

Fig 5: Bornholm's Path to 100% Renewable Energy: The EcoGrid 2.0 Architecture and Results

Bornholm Island (40,000 inhabitants) is a **living laboratory** for 100% renewable integration

EcoGrid 2.0 Architecture:

- **Generation**: Wind 30 MW, Solar ~15 MW, Biomass (cogeneration)
- **Storage**: Batteries 10 MWh, Pumped hydro 5 MW/20 MWh, Green H_2 (pilot)
- **Central EMS**: AI + Digital Twin + weather forecasting + real-time pricing
- **Smart distribution**: 1,500 smart households + V2G (150 EVs)

Measured results:

Indicator	Value
RE share 2025	55%
Peak RE reached	85%
Islanding tested	Up to 48h
CO_2 reduction	−40% vs 2010
Electricity cost	−15%
Grid losses	−8%
Customer satisfaction	92%

Table 4: Measured results

Islanding is viable with storage + demand response + forecasting. Customer flexibility is essential.

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APPENDIX 6

ADVANCED PERSPECTIVES AND ORIGINAL CONTRIBUTIONS FOR THE ALGERIAN ENERGY TRANSITION

6.1 Introduction

The critical analysis of the five preceding chapters reveals that the Algerian energy transition, while technically and economically viable, requires a more analytical and prospective approach to transcend the stage of strategic announcements toward effective implementation. This chapter aims to address this gap by proposing original contributions grounded in recent scientific advances and Algerian geoclimatic specificities. The objective is to provide actionable recommendations for policymakers, engineers, and researchers, relying on integrated systemic modeling of national energy resources [1, 2].

6.2 Quantitative Analysis of Algerian Energy Potential: A Multi-Criteria Approach

6.2.1 Spatialized Assessment Methodology

The precise mapping of Algerian renewable resources requires the adoption of advanced geostatistical methodologies combining satellite data (MODIS, Sentinel-2), digital elevation models (DEM), and spatial multi-criteria analyses (SMCA). A recent study based on the Energy Exposure Index (EEI) demonstrated that 72% of Algerian territory presents exceptional solar potential (GHI > 2200 kWh/m²/year), concentrated primarily in the wilayas of Adrar, Ouargla, Tamanrasset, and Illizi [3]. This spatialized approach enables the identification of priority zones for accelerated deployment of large-scale photovoltaic power plants, simultaneously integrating grid, relief, and accessibility constraints.

In parallel, wind resource analysis through high-resolution CFD (Computational Fluid Dynamics) modeling (500 m × 500 m) reveals an underestimated potential in the High Plateaus, where nocturnal katabatic winds can reach 8-10 m/s at 100 m height, offering potential capacity factors of 35-45% [4]. This discovery challenges classical mapping based solely on surface meteorological data and opens new perspectives for onshore wind energy in Algeria.

6.2.2 Modeling of Solar-Wind Complementarity

The intrinsic intermittency of variable renewable sources constitutes the main obstacle to their massive integration into the Algerian electrical grid, historically designed for centralized and stable production. An original contribution lies in the probabilistic modeling of spatio-temporal complementarity between solar and wind energy at the national scale. Recent work by Moradi et al. [2] demonstrates that the optimal combination of a solar park in the Sahara (Adrar) and a wind farm in the High Plateaus (Laghouat) reduces hourly production variability by 62% compared to a single source, with a negative correlation coefficient of -0.34 between annual production profiles.

This geographical complementarity, based on the anti-correlation of wind and insolation regimes, enables the definition of "optimal energy corridors" for the deployment of storage and transport infrastructure. The High Commission for Renewable Energies and Energy Efficiency (HCEERE) has integrated these results into its national strategy 2023-2030, recommending a targeted geographical distribution of renewable investments to maximize the stability of the national electrical system [5].

6.3 Advanced Integration of Hybrid Systems: Toward Intelligent Microgrids

6.3.1 Architecture of Decentralized Microgrids for Isolated Areas

Algeria has more than 10,000 localities not connected to the national grid, primarily in the Saharan South. The conventional solution through diesel generator sets presents prohibitive fuel transport costs (up to €0.80/kWh) and a high carbon footprint. An original contribution consists in the proposal of a standardized hybrid solar-wind-storage microgrid architecture, sized by multi-objective optimization (cost, reliability, emissions) via NSGA-II genetic algorithms [6].

This architecture, validated by simulation for the case of Tamanrasset, comprises:

- A 50 kWp PV generator with bipolar trackers
- A 10 kW vertical-axis wind turbine (adapted to turbulent winds)
- An 80 kWh lithium-ion storage with intelligent management by LSTM neural network
- A 15 kW backup diesel generator (load factor < 5%)

Simulation results over 20 years show an LCOE of €0.18/kWh, representing a 77% reduction compared to diesel, with 99.7% availability [6]. The HCEERE has initiated a pilot program to deploy 50 such microgrids by 2027, with joint financing from the African Development Bank and national funds [5].

6.3.2 Predictive Management by Artificial Intelligence
Real-time optimization of hybrid systems requires short-term forecasting algorithms (15 min - 4 h) for solar irradiation and wind speed. Recent advances in deep learning, particularly hybrid CNN-LSTM-Attention architectures, enable achieving forecast errors (nRMSE) of 8-12% for irradiation and 15-20% for wind, representing a 30-40% improvement over classical statistical methods (ARIMA, persistence) [7]. The integration of these forecasts into a reinforcement learning-based energy management system (EMS) (Deep Q-Network) enables an 18% reduction in storage costs and a 12% increase in self-consumption rate [8].

6.4 Energy Storage: Beyond Lithium-Ion Batteries

6.4.1 Thermal Storage with Molten Salts for CSP
While Chapter 4 explored photovoltaics, Concentrated Solar Power (CSP) with molten salt thermal storage (60% $NaNO_3$, 40% KNO_3) offers a unique intra-day to inter-seasonal storage solution. A 100 MW CSP plant with 12 hours of thermal storage can provide dispatchable production with a capacity factor of 55-60%, comparable to a conventional thermal plant [9]. For Algeria, where Direct Normal Irradiance (DNI) exceeds 2500 kWh/m²/year in the Sahara, the LCOE of CSP with storage is projected at 7-9 cents/kWh by 2030, becoming competitive with natural gas for baseload production [10].

The HCEERE has identified three priority sites for CSP pilot plants: Hassi R'mel (Laghouat), Ouargla, and Adrar, with a cumulative target of 500 MW by 2030 [5].

6.4.2 Power-to-X and Green Hydrogen: Export Vector
Algeria's excess summer solar production (potential of 40 TWh/year unconsummed) can be valorized through high-temperature electrolysis (SOEC) coupled with CSP, with electrolytic efficiency of 85-90% [11]. The produced green hydrogen, with a target cost of €2-3/kg by 2030, constitutes a strategic export vector toward Europe via the SoutH2 corridor, currently under negotiation with European partners (Snam, VNG, Verbund) [12]. This approach transforms Algeria from a natural gas exporter into a decarbonized hydrogen exporter, preserving foreign revenues while diversifying the national economy.

6.5 Original Contribution: Intensive Agrivoltaics in Arid Environments

6.5.1 Concept and Modeling
Agrivoltaics, the association of photovoltaic electricity production and agriculture on the same land area, takes on an original dimension in the Algerian context characterized by aridity and water scarcity. A coupled thermo-hydric modeling (Richards equations + radiative balance) demonstrates that the partial shading of PV panels (transmittance of 30-50%) reduces evapotranspiration by 25-40% and lowers soil temperature by 3-5°C, creating a microclimate favorable to the cultivation of halophyte plants (Salicornia, Salsola) and drought-resistant legumes (chickpea, lentil) [13].

6.5.2 Energy and Economic Balance
An agrivoltaic system of 1 MWp on 2 hectares in the Ghardaïa region produces:

- 1800 MWh/year of electricity (capacity factor 20.5%)
- 8 tonnes/year of halophyte biomass (yield 4 t/ha/year)
- 40 m³/year of biogas through biomass methanization (5 m³/t)

The LCOE of electricity is reduced by 12% compared to conventional ground-mounted PV, thanks to agricultural revenues and reduced panel cleaning costs (shading limiting dust accumulation) [13]. This approach simultaneously addresses energy, food, and environmental challenges, combating desertification through soil fixation.

6.6 Integration into the National Grid: Toward an Algerian Smart Grid

6.6.1 Specific Technical Challenges

The integration of 15 GW of renewables by 2035, as planned by the PNEREE, requires a profound overhaul of the Algerian electrical grid. Specific challenges include:

- The absence of HVDC lines for transport from the Saharan South to the North (where 70% of demand is concentrated)
- High grid loss rates (14-16% vs. 6-8% world average)
- A radial structure with low flexibility, inherited from centralized planning

6.6.2 Proposed Smart Grid Architecture

An original contribution proposes a three-level hierarchical architecture:

- National Level: Superposition of a 400 kV meshed grid with 2 × 800 kV HVDC lines (Sahara → North), controlled by VSC (Voltage Source Converter) stations for dynamic stabilization [14].
- Regional Level: Intelligent substations with phase-shifting transformers and FACTS (STATCOM, SVC) for voltage and reactive power regulation [15].
- Local Level: Community microgrids with smart meters, demand management through dynamic pricing (Time-of-Use), and V2G (Vehicle-to-Grid) integration for electric vehicles [16].

The deployment of this architecture, estimated at USD 8-10 billion over 10 years, requires a structured public-private partnership and the adoption of IEC 61850 standards for the interoperability of control systems [17].

6.7 Strategic Recommendations and Roadmap

6.7.1 Short Term (2024-2027)

- Finalization of the regulatory framework for self-consumption and grid injection
- Deployment of 50 pilot microgrids in isolated areas
- Creation of a sovereign green fund for renewable energy financing (capitalization USD 2 billion)

6.7.2 Medium Term (2027-2032)

- Construction of HVDC Sahara-North lines and Maghreb-Europe interconnection
- Installation of 2 GW of CSP with thermal storage
- Launch of pilot green hydrogen production (100 MW electrolysis)

6.7.3 Long Term (2032-2040)

- Achievement of 40% renewables in the electricity mix
- Commercial export of green hydrogen to Europe (1 Mt/year)

- Development of a local industry for PV module, wind turbine, and electrolyzer manufacturing

6.8 Conclusion

This study has demonstrated that the Algerian energy transition, far from being a simple technological substitution, constitutes an opportunity for deep economic and industrial restructuring. The original contributions presented—spatialized multi-criteria modeling [2, 3], intelligent hybrid microgrids [6], arid agrivoltaics [13], and integrated Smart Grid architecture [14, 15, 16, 17]—offer concrete solutions to the challenges of intermittency, grid integration, and economic viability. The success of this transition will crucially depend on coordination between national institutions (HCEERE, Sonelgaz, Sonatrach), international partners, and the Algerian scientific community, within a framework of transparent governance and citizen participation.

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NOMENCLATURE

AC – Alternating Current
CAPEX – Capital Expenditure (Investment Cost)
OPEX (Operational Expenditure)
CCGT – Combined-Cycle Gas Turbine (gas–steam combined cycle)
CdTe – Cadmium Telluride
CIGS – Copper–Indium–Gallium–Selenium
CSP – Concentrated Solar Power
DC – Direct Current
RES – Renewable Energy Sources
GHI – Global Horizontal Irradiation
IEC – International Electrotechnical Commission
LCOE – Levelized Cost of Energy
MPP – Maximum Power Point
MPPT – Maximum Power Point Tracking
OPEX – Operating Expenditure (Operating Cost)
OTEC – Ocean Thermal Energy Conversion
PN – Positive–Negative Junction (semiconductor)
PV – Photovoltaic
PWR – Pressurized Water Reactor
STEP/PSH – Pumped-Storage Hydropower (pumped energy transfer station)
Pi: power of device [W]
ti: Device usage time [h/d]
Controller efficiency ηc
Inverter efficiency ηinv
Maximum discharge depth DOD
PSTC: nominal power of the module [W]
Heff: effective daily irradiation [h]
Loss factor: temperature, dust, wiring (≈0.75–0.85)
N modules Number of modules required:
Nj desired number of days of battery life
Vbat: system voltage [V]
DOD: maximum discharge depth (%)
Cbat battery capacity