Master Thesis

Escola Tècnica Superior
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Analysis of a Total Integration of Renewable Energy in Catalonia Through a Dynamic Virtual Power Plant Model and the Use of Hydrogen as a Method of Energy Production Stabilization

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Acknowledgment

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Finally, I would like to acknowledge all the individuals who participated in this study, my friends that I made in the university and my friends in my job, as their contributions were vital to the success of this research. Without their valuable insights and cooperation, this thesis would not have been possible. I am sincerely grateful for their time, effort, and willingness to participate.

Abstract

Several models and scenarios have been developed to understand the dynamics and implications of integrating renewable energy technologies into the grid. In this document, the focus was on photovoltaic (PV), wind power, hydropower, and hydrogen systems facing Catalonia's electric demand.

In the process to elaborate a functional model, several factors are taken into account such as power generation, storage, and demand, aiming to minimize the levelized cost of energy (LCOE) and identify cost-effective solutions. The importance of the impact of renewable energy shares, the role of nuclear and gas facilities, and the potential of hydrogen as a storage medium and versatile energy carrier are relevant topics that incorporates new variables and corresponds to the increase of the diversity of sources needed to face climatic change.

Considerations such as production limits, hydrogen limited to absorbs electricity and generation in function of the grid requirements, LCOE dynamics, and policy frameworks were also emphasized in order to develop a general system that supports to understand how the natural response of the system in changes on demand in function of the available sources could be.

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1 Introduction

The integration of renewable energy sources into the grid is a key focus in the pursuit of a sustainable and clean energy future. In this document, several scenarios are explored and developing a model to understand the dynamics and implications of incorporating different renewable energy technologies, such as photovoltaic (PV), wind power, hydropower, and hydrogen systems.

Examining the optimization of energy systems considering factors such as power generation, storage, and demand. The model takes into account the capacity factors, energy production, and operational constraints of each technology, as well as the costs associated with capital expenses (CAPEX) and operational and maintenance expenses (OPEX). The objective was to minimize the levelized cost of energy (LCOE) and find the most cost-effective solutions for each scenario.

Through the model, the behaviour of the grid is analysed under different renewable energy shares, considering the role of nuclear power plants, gas facilities, and the progressive increase of renewable sources. The results are shown as the impact on the installed capacity, capacity factors, and LCOE as the renewable share increased.

Furthermore, is analysed the potential of hydrogen systems as a storage medium and their integration with renewable energy sources. Hydrogen was considered both as a means to stabilize the grid and as a versatile energy carrier for applications such as electric vehicles, backup storage, and heating systems.

During the simulation is also highlighted the importance of considering factors such as grid losses, trade of hydrogen, the impact on LCOE when incorporating hydrogen systems into renewable plants, and the need for supportive policy and regulatory frameworks.

Overall, this document provides valuable insights into the complex dynamics of renewable energy integration, energy storage, and the potential of hydrogen as an enabler for a more sustainable energy system. By further studying grid behaviour, cost dynamics, and policy frameworks, we can advance our understanding and accelerate the transition to a cleaner and more resilient energy future.

This project has been undertaken in collaboration with Danilo Silva Lévano and his research project titled "Analysis of a Total Integration of Renewable Energy Through a Dynamic Virtual Power Plant Model and the Use of Hydrogen as a Method of Energy Production Stabilization." The project provides a comprehensive comparison of various autonomous communities. The collaboration with Mr. Silva Lévano has greatly enriched the research and facilitated a deeper understanding of the subject matter.

2 Background and definitions

2.1 Renewable energy sources

2.1.1 Biomass and biofuels

Biomass

A biomass source is classified as the matter from organic organisms, that under certain treatment is possible to extract latent energy to obtain useful work. There are different ways to convert the latent energy contained in the organic matter into the energy needed for our necessities.

First, is important to consider that biomass energy is one of the most ancient sources to obtain energy, this last sentence is given by historical roles until the early 19th century where biomass was the main source in industrial countries [1], mainly matter used includes wood, charcoal, and agricultural residues.

Recently, in 2021 has been estimated that approximately 25 EJ were used for cooking and heating [2], this corresponds mainly in developing economies in Africa and Asia where the access to clean cooking is difficult mainly in rural zones.

In fact, biomass[1] must be differentiate of hydrocarbon sources in the way that the first one comes from sources that can be available on a renewable basis and managed like forests, crops, agricultural surplus, municipal organic wastes, etc.

In the case of hydrocarbon sources comes from oil reservoirs that initially were originated by organic matters with a very low (almost none) renewable basis to face human necessities.

Biomass goes through several steps from the natural state. Actual manufacturing processes include certain conditions to conditionate the matter according to technical requirements to improve energy efficiency conversion, the main steps are the following ones:

- **Primary bioenergy:** it refers to the biomass in nature before conversion.
- **Final bioenergy:** it is related to the final state of the matter (solid, liquid, or gaseous fuels) before using directly for a given application.

[1] Like biofuels in detail in the next paragraphs.

- **Useful bioenergy:** it refers to the net energy (excluding losses) obtained from the biomass source like electricity and heat.

Biofuels

The terminology for biofuels indicates all kind of biobased products (solid, liquid, or gaseous substance) produced from natural products, nowadays bio-oil, bioethanol, biodiesel, and biogas are examples of the modern form of biofuels [3].

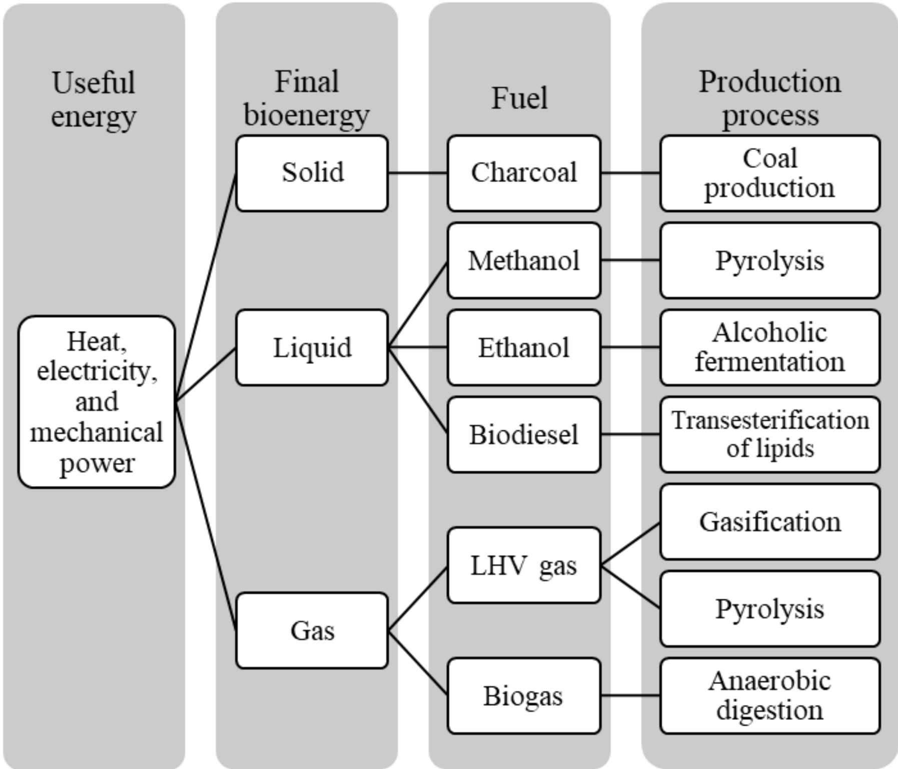


Illustration 1. Biofuel types and production processes. Own adaptation from [4].

Illustration 1 shows the useful energy obtained from solid, gas, and liquid estates; each one of them is treated from different production processes that correspond of certain conversion type as follows:

- **Thermochemical conversion:** Refers to the decomposition of biological matter by partial or total oxidation, notice that thermal energy is an important agent that influences the final products [5].
- **Physicochemical conversion:** It is related to the physical organic structure breakdown; steam explosion pre-treatment is one of the most extensive methods used for decomposition of biomass matter [6].

- **Biological conversion:** Regarding to the decomposition of the organic matter through biological organisms that breakdown complex organic structures, one of the most used methods is anaerobic digestion.

Notice that for the case of solid fuels, the raw biological matter can be used as well (referring to traditional biomass uses), other solid fuels are straw bales, briquettes, wood chips, and wood pallets.

2.1.2 Geothermal

This type of energy is given by the thermal energy under earth crust. That energy has been originated by the planet formation and the decay of radioactive materials (like potassium, thorium, and uranium). Under certain geological conditions thermal energy can be used to produce electricity, heat, and for seasonal storing.

During Earth's formation, certain materials were formed by supernovas[2], ejecting a big number of elements to the space (from lightweight until heavy atoms), all this material formed clouds that collapsed under gravity effects to form planets. In Earth's formation, this process captured heavy materials at high temperatures that remains until these days releasing heat to upper layers.

It is a fact that Earth's structure is formed by several layers under terrestrial crust, each layer has it owns properties and characteristics due to the rock formation and geological behaviour along time.

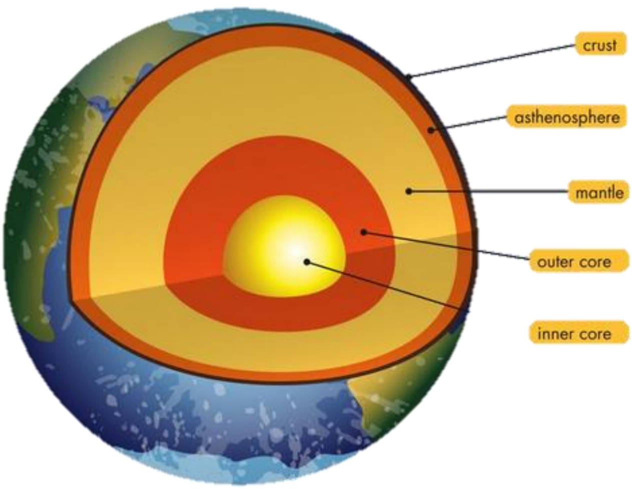


Illustration 2. Layers of the Earth. Eboch, M. M. (2019). Geothermal Energy. United Kingdom: Raintree Publishers.

[2] It is a star's explosion when it consumes all fuel in the core.

Illustration 2 shows the main layers from the surface until the Earth's core, thickness of each layer is not well defined depending on the location of the reference point on the planet's surface and historical region formation, Table 1 indicates approximately some estimated characteristics of each of them.

Layer	Thickness	Average temperature
Crust + lithosphere	100 km	500 °C
Asthenosphere	150 km	1355 °C
Mantle	2642 km	2770 °C
Outer core	2245 km	4410 °C
Inner core	1180 km	+ 5000 °C

Table 1. Thickness and average temperatures for different Earth's layers. Own adaptation from [7].

It is evident that temperature increases with depth, the relationship between temperature is not lineal but it is estimated that the gradient is around 0.15 – 0.30 °C/km for the lithosphere layer, this is subject to tectonic movements that sets different gradient due to the constant displacement of material from upper layers to lower ones and vice versa.

Regarding to the application of geothermal energy, it can be classified in function of the enthalpy of the resource, this last is directly influenced by temperature as well as follows [8]:

- **Very low enthalpy system:** it is related to temperatures around 5 – 25 °C and corresponds to shallow volumetric spaces, in contrast, this kind of systems have a good performance for seasonal storing using heat pumps[3].
- **Low enthalpy system:** it is characterized for operates at a range of temperatures between 30 – 90 °C and using water directly from geothermal well, this kind of system can work with (through cavitation effect[4]) or without phase change. Applications are given for heating and home climatization.
- **Medium enthalpy system:** it is regarded to reservoirs with a temperature in the range of 90 – 150 °C, the relative elevated temperature allows to use it in household heating and for electricity production as well (through binary cycles).

[3] An example of this is storing heat in summer to use it in winter.
[4] Depending on literature, this can be called flash steam water.

- **High enthalpy system:** this kind of sources are suitable for electricity applications where temperatures over than 200 °C are needed to impulse a steam turbine, there are several sub-systems to take advantage of remaining energy before reinjecting to the reservoir like binary cycles (using isobutane or isopentane as thermodynamic fluid).

2.1.3 Hydraulic

Hydropower is the source of water potential between two points at different height, allowing water to move transforming potential energy into kinetic one, this kind of energy is needed to impulse the turbines that at the same time generates electricity through a generator connected to the shift.

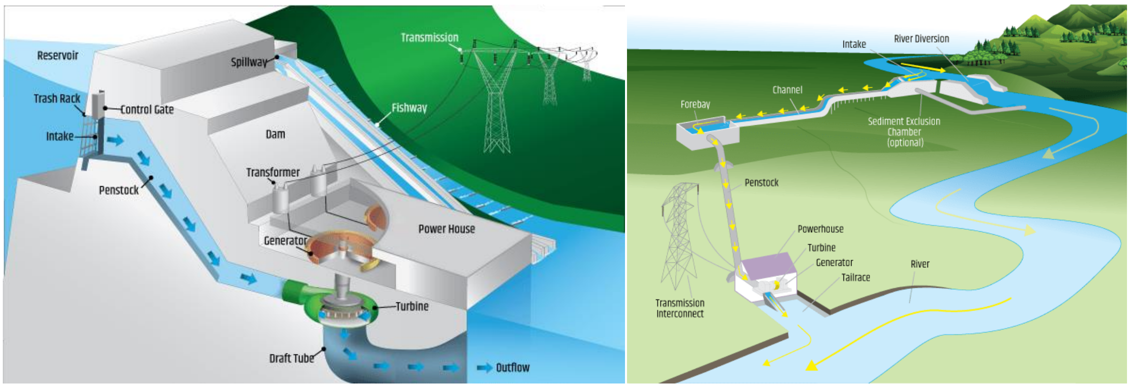


Illustration 3. Two main facilities for hydropower installations. Office of Energy Efficiency and Renewable Energy.

Considering they can be in different sizes and forms, two main types can be differentiated: Impoundment facility and run-of-river one, the first one employs a dam to storage water into a reservoir and releases through the penstock to a turbine, this facility is given for big hydropower systems; run-of-river installation uses the usual water flow from a river derivation in a channel until a powerhouse where water impulses a turbine, this system is for low energy generation.

A third category is a pumped facility, the structure is like an impoundment facility, but a pumping system is incorporated to take water from the lower reservoir to the upper one, this kind of architecture responds to absorb grid surplus and using the reservoir as an energy storage tank to use it in high demand hours.

2.1.4 Photovoltaic

This is one of the most used resources used and commercially known in the market, both for residential applications and high-power facilities. The main energy source is given from Sun, where photons are generated through the fusion of hydrogen atoms to generate helium in the core. These particles move through the Sun's layers before to be ejected to the space. Some of them reach the Earth's surface where solar modules absorb that energy and transform it into electricity, this last process is the photogeneration effect.

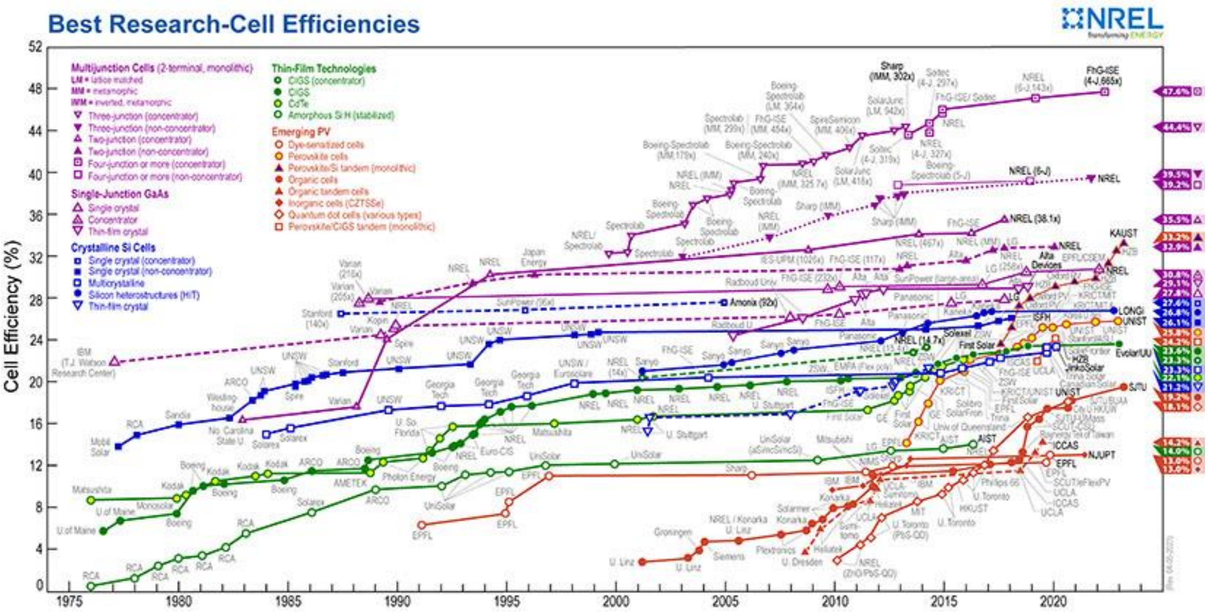


Illustration 4. Technologies and cell efficiencies developed. This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO. 2023.

Illustration 4 joins all type of cell technologies, their improvement along time and actual efficiency status until 2023. It is interesting to note that commercial PV modules are just one of several technologies showed before, for the last report there are reported 26 types of cells grouped in 5 big families [9].

- Multijunction cells
- Single-junction gallium arsenide cells
- Crystalline silicon cells
- Thin-film technologies
- Emerging photovoltaics

Table 2 (given below) shows the maximum efficiency reached by technology categorized by family, and year of the test. All these values have been evaluated in laboratory conditions according to IEC 60904-3, the standard test conditions are given for a cell at a temperature of 25 °C, irradiance of 1000 W/m^2, and for a spectral distribution AM1.5.

Family	Semiconductor	Highest efficiency	Year
Multijunction cells	Three-junction with concentration	44.40%	2013
	Three-junction without concentration	39.46%	2021
	Two-junction with concentration	35.50%	2017
	Two-junction without concentration	32.90%	2020
	Four-junction (or more) with concentration	**47.60%**[5]	**2022**
	Four-junction (or more) without concentration	39.20%	2019
Single-junction gallium arsenide cells	Single crystal	27.40%	2015
	Concentrator structure	30.80%	2022
	Thin-film crystal	29.10%	2018
Crystalline Si cells	Single crystal with concentration	27.60%	2007
	Single crystal without concentration	26.10%	2018
	Multicrystalline	24.40%	2020
	Silicon heterostructures	26.81%	2022
	Thin-film crystal	21.24%	2014
Thin-film technologies	CIGS[6] with concentration	23.30%	2014

[5] It is the highest efficiency reached for a single technology; test was performed in Fraunhofer Institute for Solar Energy System's facility.
[6] Copper Indium Gallium Selenide.

	CIGS without concentration	23.60%	2023
	CdTe[7]	22.10%	2015
	Amorphous Si:H[8]	13.00%	2015
Emerging PV	Perovskite cells	25.80%	2022
	Perovskite/Si tandem	33.20%	2023
	Organic	19.20%	2023
	Organic tandem	14.20%	2019
	CZTSSe[9]	13.00%	2021
	Dye-sensitized	13.00%	2020
	Quantum dot	18.10%	2020
	Perovskite/CIGS tandem	24.20%	2020

Table 2. Highest efficiencies by cell technology. Own adaption from [9].

Photovoltaic effect

In a general simplified description, a solar cell construction consists of an absorbent substrate to catch photons. In Table 2 has been showed several substrates and architectures of solar cells, for instance, most usual material is silicon doped semiconductor in commercial applications, in one hand, base material is doped with boron (or gallium) to obtain a p-type semiconductor[10], otherwise, an n-type semiconductor[11] is fabricated adding phosphorus (or arsenic).

[7] Cadmium Telluride.
[8] Hydrogenated Amorphous Silicon.
[9] Copper Zinc Tin Sulphur-Selenide
[10] It can be called "electron acceptor" due to the capability to receive electrons on their electronic configuration.
[11] Depending on literature, it can be called "electron donor" due the excess of electrons on their electronic configuration that allow to share easily.

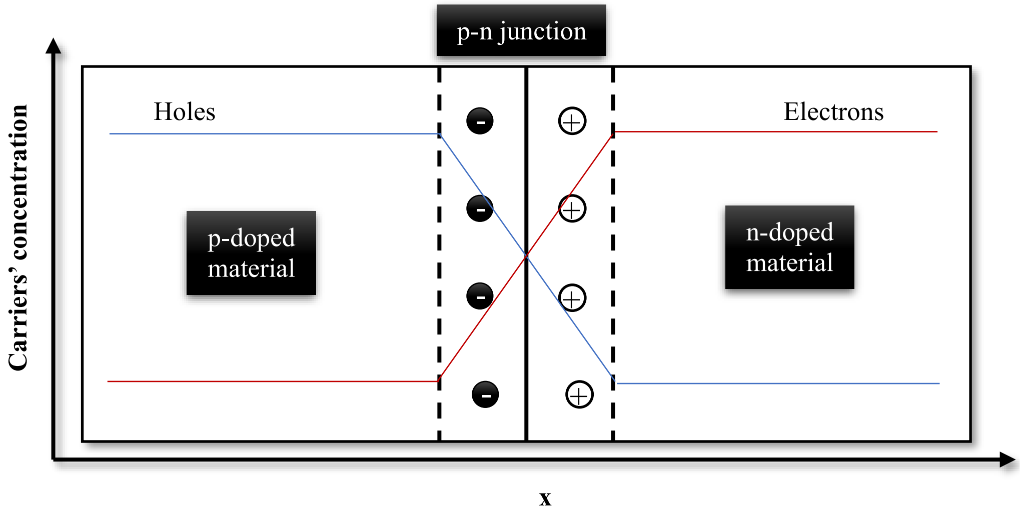


Illustration 5. p-n junction and carriers' concentrations.

In Illustration 5, considering both, n-type and p-type semiconductors, a p-n junction is formed, this one is a space where excess of holes and electrons diffuse and recombine generating an electrically stable zone. The structure is the base for a solar cell and diodes as well, to understand better how a solar cell (and a solar panel) works, is needed to introduce the concept of valence, conduction, and forbidden bands.

- **Valence band:** is the last layer for an atom, this one is the highest quantum position for an electron around the nucleus, most chemical reactions are given sharing electrons through this layer and allows the main characteristics for an atomic behaviour.
- **Conduction band:** is a quantum space outside the atom where the effects of the nucleus does not affect the electron mobility, due to this, a not bounded electron can move freely through a crystalline structure until recombines.
- **Forbidden band:** also called forbidden energy gap. It is the space between valence and conduction bands where is a zero probability to find an electron. In bands theory is useful allowing to know how bounded a valence band with the atom's nucleus is. In other words, as greater the forbidden band, more isolated the material is.

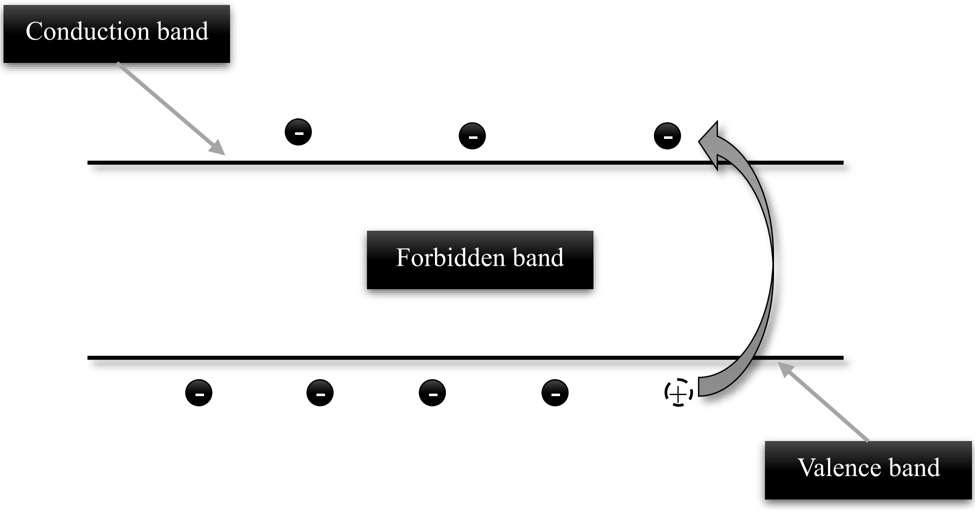


Illustration 6. Visual description of the different quantum bands.

In the case of an excited electron in the valence band, it acquires a higher energetic state above the valence band energy value, as a result, this electron "jumps" from the valence band to the conduction band with the most suitable energy level. The opposite phenomenon is also applied to this, when an electron loses energy, it moves from the conduction band to the most suitable valence band's quantum level, a graphic description is given in Illustration 6.

Previous paragraphs indicate the main physical mechanism for an electron's diffusion. A solar cell architecture applies the previous concepts considering in a semiconductor like silicon p-n junction, an electron is excited through the energy of an incident photon. During this process, is formed an electron-hole pair[12] that diffuses through semiconductor until it splits due to local electric fields, the electron reaches the conduction band and moves to the Electron Transport Layer (ETL) and by other hand, holes diffuse to the Hole Transport Layer until the respective collectors and complete the electrical circuit.

[12] For each free electron formed, a hole is created as well.

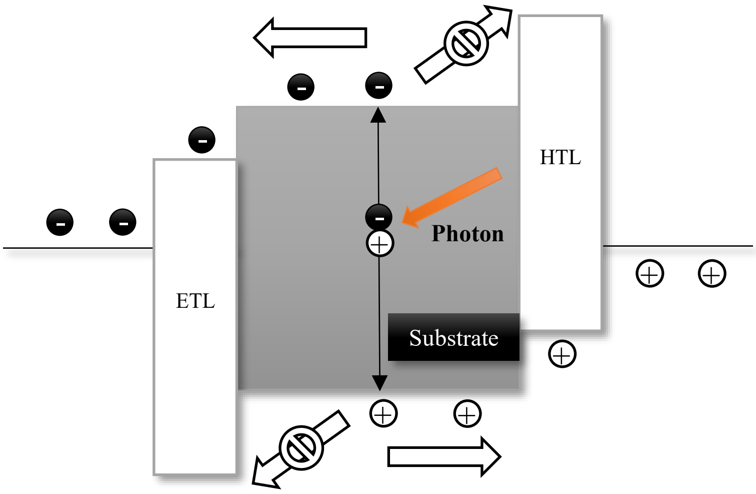


Illustration 7. Simplified band diagram considering ETL and HTL.

In Illustration 7 is shown the main architecture for a solar cell, where ETL and HTL works as a conductors for electrons and holes respectively, at certain point those work as filters not allowing to cross electrons (for the case of the HTL) and holes (for ETL) to recombine in a lower quantum state, this kind of materials improves the efficiency of the solar cell.

Electrical parameters

Apart on the physical method of energy production, there are several electrical characteristics to evaluate a solar cell performance:

- **Reverse saturation current density** [J_o]**:** is the type of current per surface given by the own structure of the semiconductor and represents the current that would flow through the solar cell under reverse bias in complete darkness. This parameter is a current opposite of the photocurrent and depends on different parameters as follows:
  - Diffusion length of the charge carrier
  - Diffusion coefficient of the charge carrier
  - Charge carriers' density
  - Surface passivation
  - Elemental charge
  - Width of the junction

- **Photocurrent density** $\left[J_{ph}\right]$**:** is the current per surface obtained when a solar cell is illuminated and depends by the following aspects:
    - Generation rate
    - Width of the junction
    - Surface passivation
    - Elemental charge
- **Short circuit current density** $[J_{sc}]$**:** is a parameter of current per surface for a solar cell when the voltage between both sides of the solar cell is zero, is equal to the photocurrent generation, this value varies by temperature and incident radiation.
- **Maximum current density** $[J_{max}]$**:** is the maximum current per surface that a solar cell can provide at maximum efficiency under operating conditions.
- **Open voltage circuit** $[V_{oc}]$**:** is the voltage between positive and negative terminals obtained for a solar cell under operating conditions, it depends on the solar cell temperature, short circuit current and dark current density.
- **Maximum voltage** $[V_{max}]$**:** is the maximum voltage that a solar cell can reach at maximum efficiency under operating conditions.
- **Fill factor** $[FF]$**:** is the ratio between the area projected between maximum current and voltage in relation to the area projected by open circuit voltage and short circuit current.

$$FF = \frac{V_{max}J_{max}}{V_{oc}J_{sc}} \qquad \textbf{Eq. 1}$$

- **Efficiency** $[\eta]$**:** indicates the ratio of energy transformation from incidence radiation, it depends on the fill factor, open circuit voltage, short circuit current, irradiance, and the solar cell temperature.

$$\eta = \frac{FF \cdot V_{oc}J_{sc}}{P_{ligth}/A_{cell}} \qquad \textbf{Eq. 2}$$

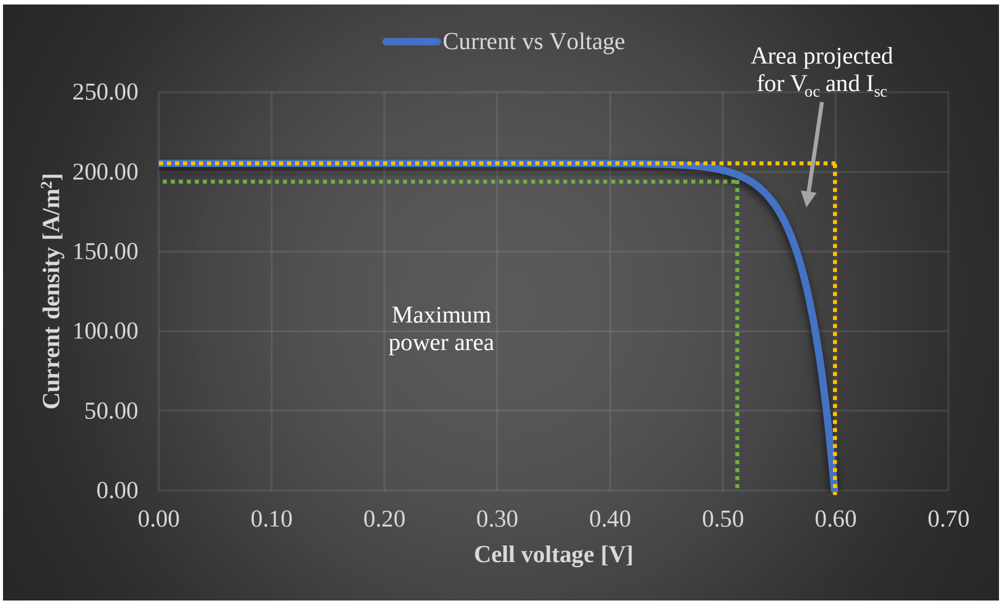


Illustration 8. Fill factor for a single solar cell.

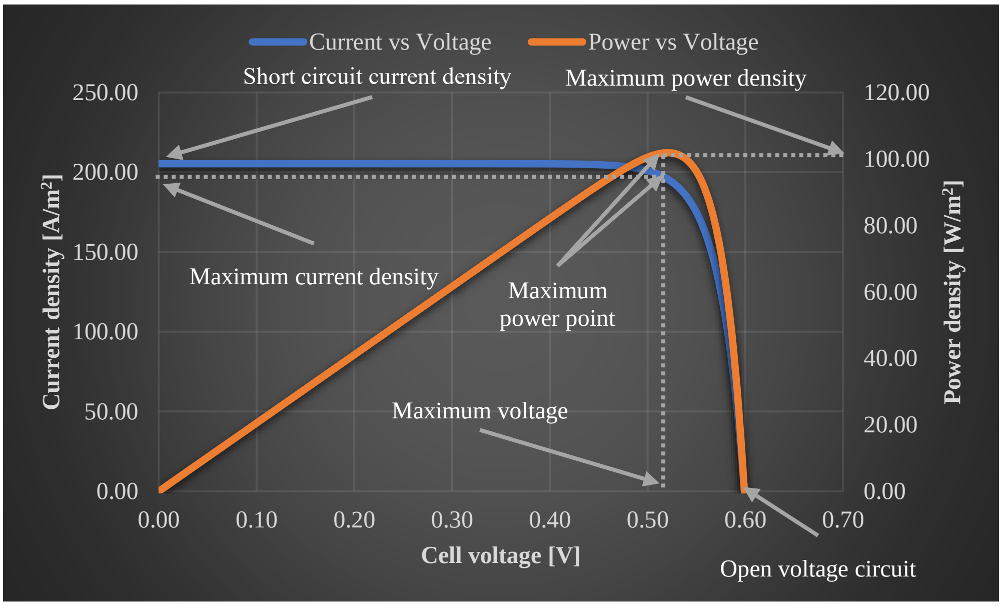


Illustration 9. Current and power density vs cell voltage for an ideal solar cell.

Illustration 8 and Illustration 9 shows the main parameters described previously, notice that the maximum power point does not indicates voltage and current density are the extreme values but the combination of both to produce the maximum power possible for a given condition, this means that for each variation on temperature and irradiation the curve tends to change and the maximum power point changes as well.

Ideal and real solar cell's electric circuit

For modelling a solar cell device, usually involves certain approaches to define it and simulates its behaviour using an equivalent electric circuit; there are two main approaches, first is the ideal solar cell model and the second is the real one. This last incorporates a higher level of complexity due to several factors and for non-predictable components.

By one hand, ideal case model represents the most basic circuit scheme represented by a current source in parallel with a diode, the model assumes that solar cells produce constant current regardless of the load connected to it.

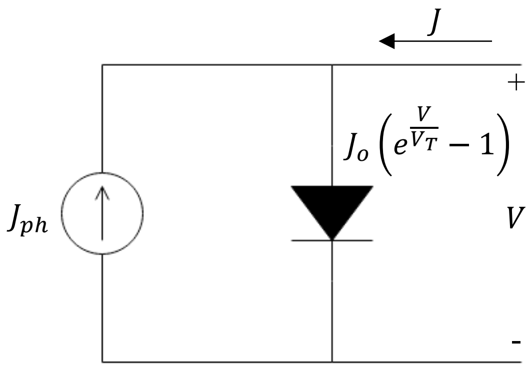


Illustration 10. Ideal solar cell equivalent circuit model.

$$J = J_o\left[e^{\left(\frac{V}{V_T}\right)} - 1\right] - J_{ph} \qquad \textbf{Eq. 3}$$

For the given equivalent circuit, the diode represents the junction between p-type and n-type semiconductors in a solar cell. The current source is the constant current generated by the solar cell under solar radiation, and it is unaffected by the load connected.

A real solar cell, by other hand, takes into account additional elements that are present in practical situations and it is affected by constructive manufacturing processes and material defects.

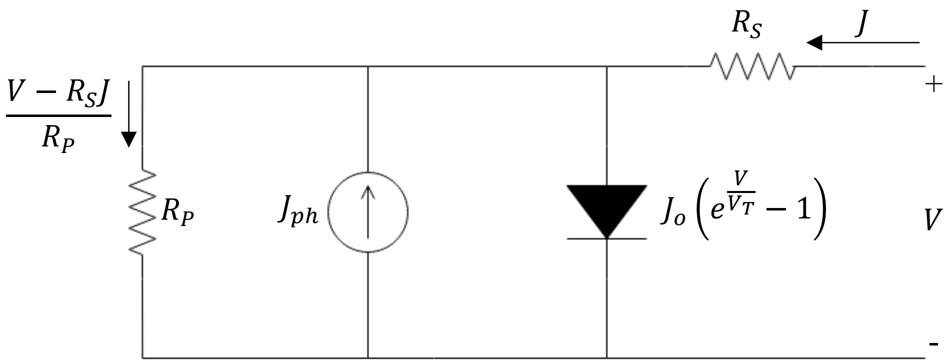


Illustration 11. Real solar cell equivalent circuit model.

$$J = J_o\left[e^{\left(\frac{V - R_S J}{nV_T}\right)} - 1\right] + \frac{V - R_S J}{R_P} - J_{ph} \qquad \textbf{Eq. 4}$$

The difference between both equivalent circuits is the series resistor and shut resistor (in parallel to the diode), the complexity for solving this model is due to the dependence of the current density itself to evaluate the voltage drop through the parallel resistance and the diode branch, for this reason numerical methods are needed to solve it.

- **Series resistance:** this is more related to the material's response when current is generated, diffused, and collected. The overall consequence is a voltage drop in contrast to an ideal solar cell. In a laboratory is possible to determine this value as the derivative of current density over voltage for very low voltage and low illumination.
- **Shunt resistance:** it is related to manufacturing process where certain current density goes through another path and as a result, we can obtain a drop current density compared to an ideal solar cell. In a laboratory is possible to determine this value as the derivative of current density over voltage for high voltages (near to the bias voltage) at high illumination.
- **Ideality factor:** describes if the behaviour of the solar cell is like a diodes' one that are theoretically predicted. A perfect solar cell's ideality factor is 1 but in real cases, usually, this value does not exceed the value 2, nevertheless when it happens some further studies are needed due it is difficult to associate in terms of classical transport mechanisms associated with the junctions [10]. In terms of determining this value, we can take Eq. 4 for dark current density, at this point it is possible to neglect the "-1" and R_P terms to simplify the process, developing logarithm properties and isolating the "n" expression.

$$n = \frac{qV}{kT \ln\left(\frac{J}{J_o}\right)}$$ **Eq. 5**

Points in common for ideal and real solar cells are the photocurrent density (current source) and the dark current density (diode), this last is the current generated by the solar cell due thermal excitation in total darkness.

Independently on the circuit model, the reverse saturation current density and photocurrent density can be defined in function of the cell's dimensions and characteristics, the most general case is considering a short solar cell with a passivated surface.

$$J_o = q\frac{D_n}{W_p}n_o \cdot \frac{S_f}{S_f + \frac{D_n}{W_p}} + q\frac{D_p}{W_n}p_o \cdot \frac{S_b}{S_b + \frac{D_p}{W_n}}$$ **Eq. 6**

$$J_{ph} = \frac{1}{2}qG\left(W_p \cdot \frac{\frac{S_f}{D_n/W_p} + 2}{\frac{S_f}{D_n/W_p} + 1} + W_n \cdot \frac{\frac{S_b}{D_p/W_n} + 2}{\frac{S_b}{D_p/W_n} + 1}\right)$$ **Eq. 7**

2.1.5 Solar thermal

Like photovoltaic technology, solar thermal uses Sun's photons to generate energy but thermal energy instead of electrical one, this kind of technology has several practical uses nowadays from cooking until high energy generation, in residential applications are designed to provide climatization and domestic hot water.

Radioactive spectrum

For a solar thermal installation, not only orientation or slope are the mainly parameters to consider for a collector design but also the radioactive spectrum, selective materials, fluid displacement, and distribution in the system are some considerations needed.

The radioactive spectrum is related to the wavelength profile emitted by a body, in fact, Sun emits practically in all wavelengths but is interesting to consider that just some of them are useful in thermal applications, specifically mid and long wavelengths (visible spectrum and infrared).

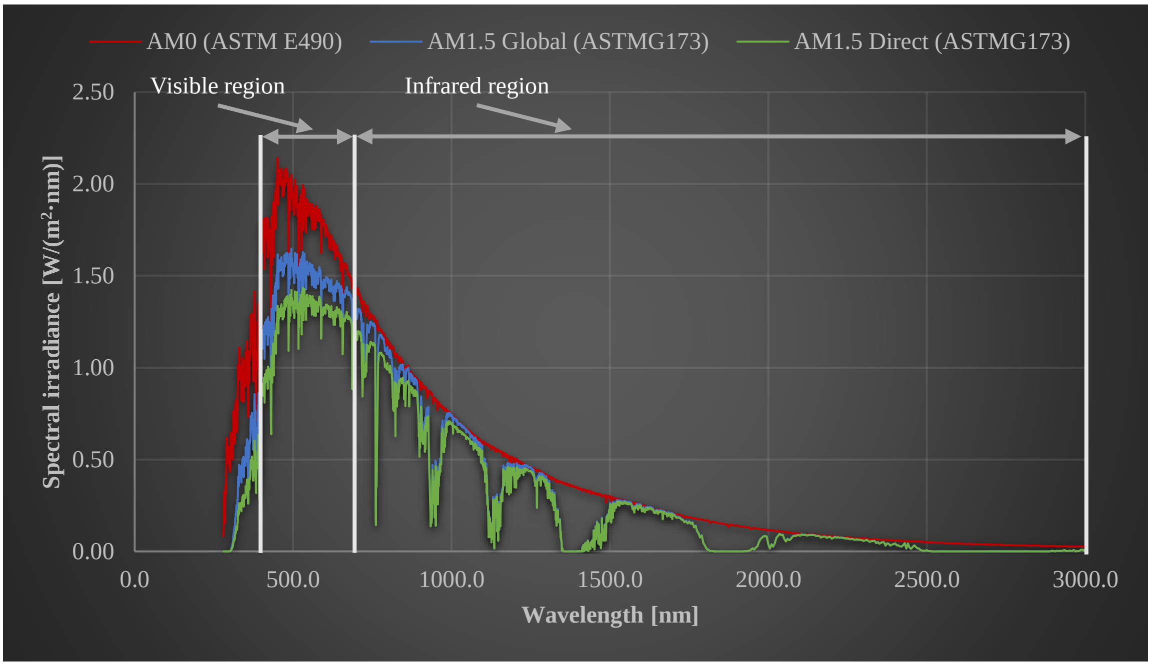


Illustration 12. Standard solar spectrum at different conditions. Data is courtesy of the National Renewable Energy Laboratory, Golden, CO.

Illustration 12 indicates the spectral irradiance profile given for different conditions, in red corresponds on the spectral irradiation for most external atmosphere layer under to the normative ASTM E490 related to the *Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables* as a reference. Normative ASTM G173 related to *Standard Tables for Reference Solar Spectral Irradiances* at ground level are shown in colour blue and green catching all light components and the bean direct light respectively.

Approximately, the useful band gaps are visible and infrared spectrum; first one is a range from 400 – 700 nm, by other hand, infrared range is 700 nm – 10 µm [11]. This means that for the totality of the solar spectrum 42.21% is covered by visible range and 50.96% for infrared range. In fact, covering both visible and infrared spectrum it is possible to take advantage of 93.17% of the total energy available.

Radiant characteristics of materials

For a solar collector, it is important not only the capacity of absorbs solar energy but also reduce thermal losses, for this case, selective materials are needed to maximize solar absorption and minimizes thermal emissions.

Black body: naturally, every material over 0 K is capable of radiate thermal energy, the reference of that is the black body concept, this is related of the capacity of radiate at all wavelengths according to Planck's law and can absorbs all wavelengths perfectly.

- **Emissivity:** it is the fraction of the energy for a real body to radiate thermal energy compared to its equivalent black body concept.
- **Absorptivity:** it is related to the fraction of the incident energy that has been assimilated by the material and modifies its thermodynamic state.
- **Transmissivity:** it is the fraction of incident energy that does not interact in a thermal way with the material, this does not mean that can modify the direction of the incident particle inside the body.
- **Reflectivity:** it is the fraction of the incident energy that only interacts with the material surface changing its direction where at least, one of the components is normal to the surface.

The last three concepts are specially bounded in the case that for an incident charged particle energy must accomplish the energy conservation law as follows:

$$\rho + \alpha + \tau = 1 \qquad \textbf{Eq. 8}$$

Where ρ, α, and τ are the reflectivity, absorptivity, and transmissivity. This equation indicates that global energy is distributed between these three mechanisms, and depending on the material's conditions some of them can be negligible, as the case of opaque material, this indicates that for a certain wavelength (or a range of wavelengths), a particle is not able to cross it.

Low and medium temperature collectors

Design and sizes of a solar collector depends on certain variables, for one side is the thermal absorption of the energy that can be develop and by other hand is the installation necessity, for this part of sizing it is necessary to stablish water renovation and desirable temperature in the system considering all loses through tubes, pipes, storage tank (if is considered), and accessories.

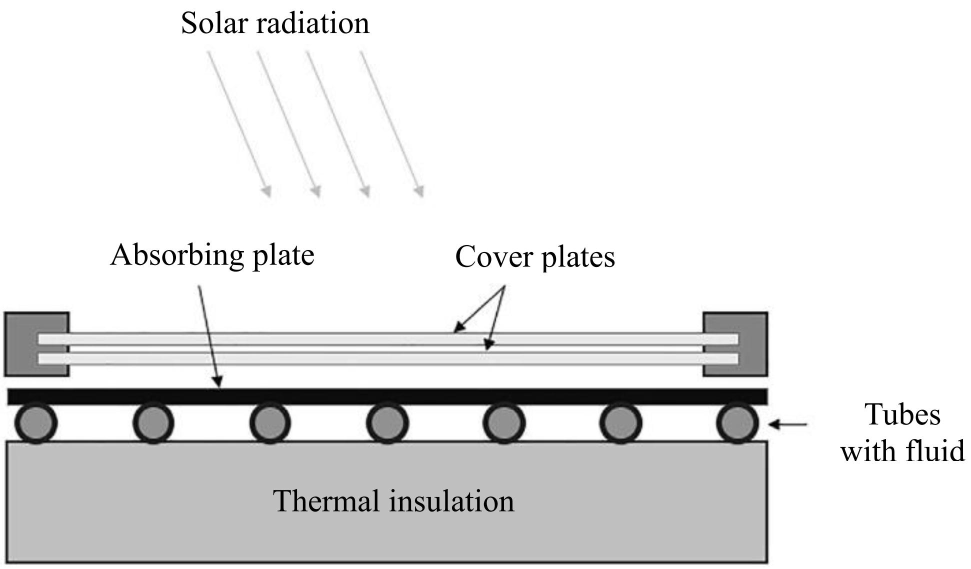


Illustration 13. Components for a typical flat plate collector [12].

In Illustration 13 is shown the most general structure to build a basic flat plate collector, in top of that cover plates are typically glass that allows short wavelengths pass through it, this cover must ensure the minimum reflection possible, and being opaque for long wavelengths (infrared range). Depending on the desirable application and temperature rise, some flat plate collector can be single, double, or with more cover plates.

The absorbing plate is made of selective material with high absorption at short wavelengths and low emissivity at larger wavelengths, this is crucial for design due that on this element is the first surface in charge of transform the energy from photons into heat (therefore increases its temperature) and at the same time it must avoid radiating an excess of heat at surroundings.

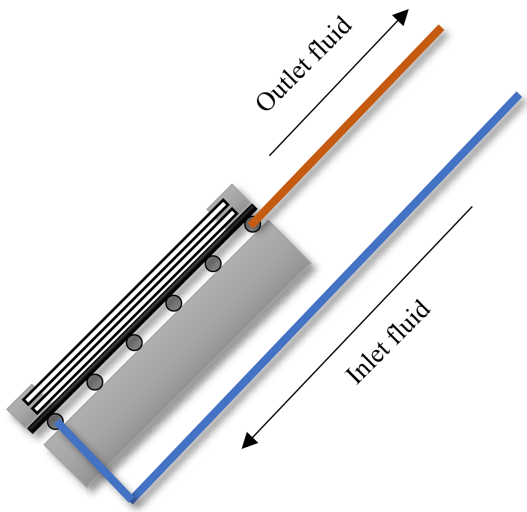


Illustration 14. Mainly flow direction in a flat plate collector.

Internal tubes contain the working fluid (water for typical applications) that absorbs thermal energy by conduction from the absorbing plate and transfers it to the fluid by convection. Illustration 14 indicates the fluid direction for a typical flat plate collector that at this point some installations require a pumping system to allow turbulent flow improving heat transfer rate and deliver to the facility, otherwise, a thermosyphon unit is used to allow the fluid moves by natural convection.

Efficiency curve and heat absorption

Energy heat transfer, from a thermodynamic point of view, can be evaluated performing an energy balance in the flat plate collector itself and from the fluid gains, most usual calculations from design consider both situations considering the fact of inlet water is already known parameter.

From the flat plate collector, an energy balance[13] is required for each component: cover plate, collector, lateral walls, isolated base, absorber, and internal tubes. All these variables are conditioned by geometric dimensions and material constitution which are covered into a global heat transfer coefficient U_L.

$$F_R = \frac{\dot{m}C_p\left(T_{fo} - T_{fi}\right)}{A_c\left[I_\alpha - U_L\left(T_{fi} - T_a\right)\right]} \qquad \textbf{Eq. 9}$$

Where F_R is related to the removal factor that can be interpreted as the effectiveness of the flat plate collector and indicates the ratio of actual heat transfer and maximum heat transfer at same conditions.

Considering this factor with overall heat coefficient and equivalent transmissivity-absorptivity of the collector we can formulate the efficiency equation.

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{\left(T_{fi} - T_a\right)}{I} \qquad \textbf{Eq. 10}$$

Eq. 10 is specific for each flat plate collector, where the left term is the maximum theoretical value that is given by the design and for the material selected. Right term indicates all kind of losses, notice that the efficiency is directly affected by the inlet temperature, and it must be like the ambient temperature to reach the maximum efficiency value.

[13] It is evaluated conduction, convection and radiation gains and losses across the material.

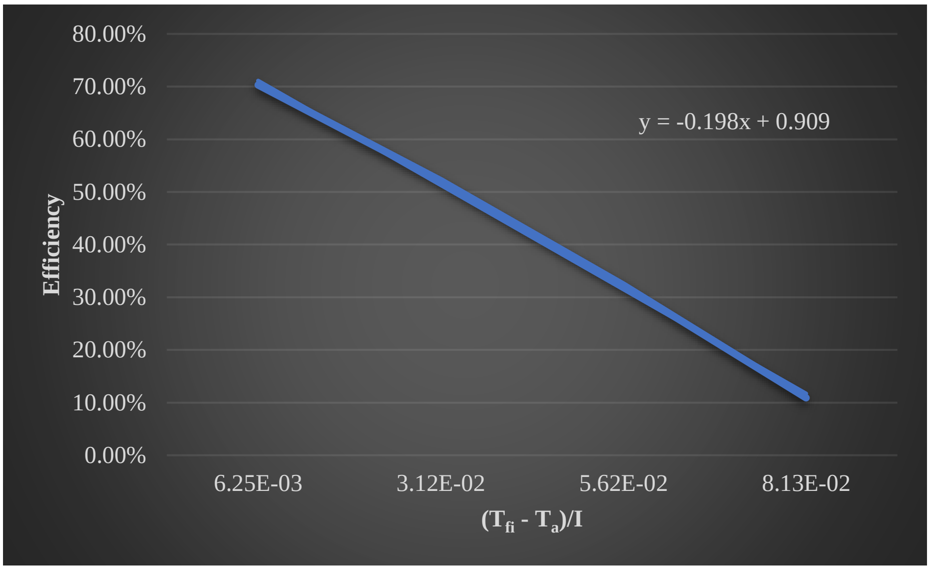


Illustration 15. Typical efficiency curve for a flat plate collector.

Illustration 15 indicates an example of a collector curve efficiency, usually can be expressed as a linear plot where the negative slope is due to losses, in this case the theoretical maximum efficiency is around 91% and the term "0.198" is the product $F_R U_L$.

$$Q_u = \eta I A_c \qquad \textbf{Eq. 11}$$

Useful energy absorbed by the collector is the product of the incoming energy from sun, collector surface and the efficiency of the device.

Another approach to evaluate the heat exchange is in function of the change of the enthalpy of the fluid that flows through the collector.

$$Q_u = \dot{m} C_p \left(T_{fo} - T_{fi} \right) \qquad \textbf{Eq. 12}$$

Enthalpy change in Eq. 12 is in function of the specific energy of the fluid and the temperature change, in this case, the structure of the collector is not considered, and this is helpful for sizing the installation.

High temperature applications

For this kind of applications, high temperature devices use a similar concept of transfer energy from sun to a fluid, the difference between both is to reach higher temperatures through the concentration of sunlight in a common point allowing the phase change of a fluid[14] and impulse a generator through a vapor turbine.

[14] Latent heat increases the amount of energy that a fluid can absorb in order to change from a phase to another.

Nowadays there are several developments of design of devices and technologies, including materials and manufacturing processes, some of the most known are as follows.

- **Parabolic trough collectors:** this kind of solar collector is one of the most mature technologies. It consists of a parabolic mirror with a focal point where a tube is located to absorb the solar energy, inside that tube water or oil is used as thermodynamic fluid.

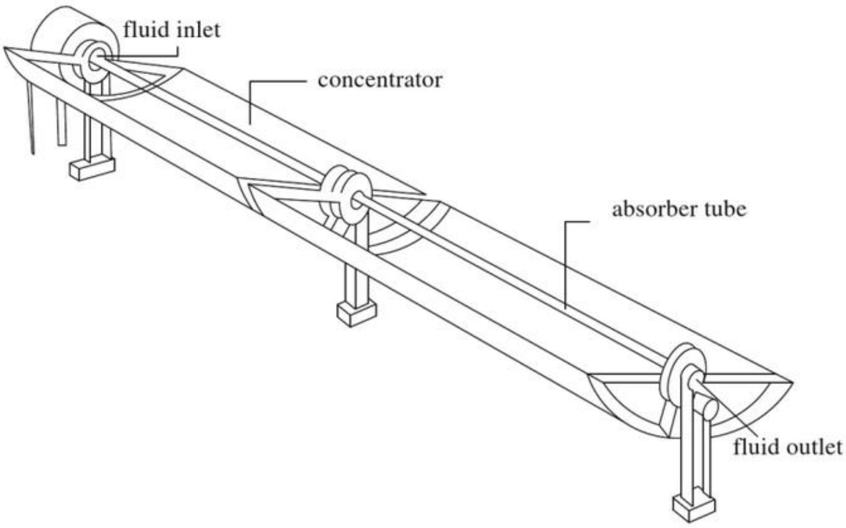


Illustration 16. Parabolic trough collector scheme [13].

- **Central solar receiver:** it consists of a group of mirrors covering a determined surface with a focal point at central tower, sizing and manage of this kind of central power needs high accurate in controlling two axis following sun's path but it offers a big amount of energy due to the high concentration factor, fluid used for this kind of facilities is molten salt due to the high fusion point.

Illustration 17. Ivanpah solar plant. Courtesy Brightsourceenergy.com, image gallery.

- **Linear Fresnel lens:** it is like parabolic trough collector, but the main difference is the use of flat mirrors (or slightly curve) instead of curve ones. Tracking system is in one axis, this represents a reduction of manufacturing costs, the global efficiency of this kind of technologies is less as well.

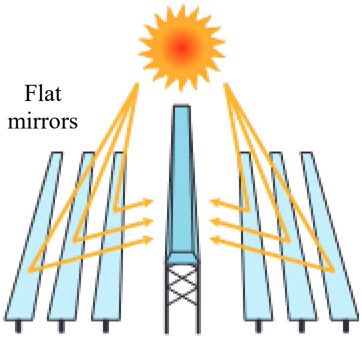


Illustration 18. Linear Fresnel representation [14].

- **Parabolic dishes:** the design of this type of solar collector is similar to parabolic antennas, where the focal point is in the centre of curvature dish where a Stirling machine is needed to generate energy, solar tracking is in two axes to follow Solar's path along the day.

Technology	Annual efficiency[15]	Space covered	Storage possibility[16]
Parabolic trough collector	15%	Large	Yes
Central solar receiver	20 – 35%	Medium	Yes
Linear Fresnel lens	8 – 10%	Medium	Yes*
Parabolic dish	25 – 30%	Small	Yes*

Table 3. Comparison of main concentrated solar plant technologies [14].

Table 3 indicates some of the main characteristic differences between the previous technologies seen before, is a fact that for parabolic trough collector the land covered is the highest one, but the relatively high annual efficiency allows to compensate the cost of installation.

[15] Efficiency related to solar conversion to electricity.
[16] Marked in * are related for some installations that depends on the land occupied and the plant configuration.

In the case of central towers, the amount of energy produced is high, but the cost of installation and operation is high as well, an additional issue is that for this kind of facilities is needed higher solar hours this is why is not very attractive in contrast of parabolic collectors. Linear Fresnel collectors and parabolic dishes are technologies in constant improvement.

2.1.6 Tidal and wave power

One interesting energy source is the use ocean waters to obtain energy, the fact that 70% of the global Earth's surface is covered by ocean indicates that how enormous amounts of energy is possible to transform into electricity, potentially, ocean energy is approximately from 20000 TWh to 80000 TWh enough to cover 100% to 400% world's demand. 535 MW is the power installed around the world with a potential to install 100 GW by 2050 [15]. That is the main challenge facing cost and make it competitive, there are mainly two types of technologies regarding of this source: tidal and wave power.

Tidal power

It is known that tildes are highly predictable, and this ensure the energy generation forecast for a mid to long-term installation, a drawback regarding to this technology is how restricted can be to a several places where the tidal must be pronounced.

Illustration 19. Rance Tidal Power Station [16].

Illustration 19 shows the Rance tidal power plant located on the estuary of the Rance river, France. It is the world's second bigger installation with 240 MW distributed in 24 bulb turbines of 5.35m diameter each and 750 m length. With a capacity factor of 40% produces approximately 600 GWh of electricity per year covering approximately 0.012% of France's demand.

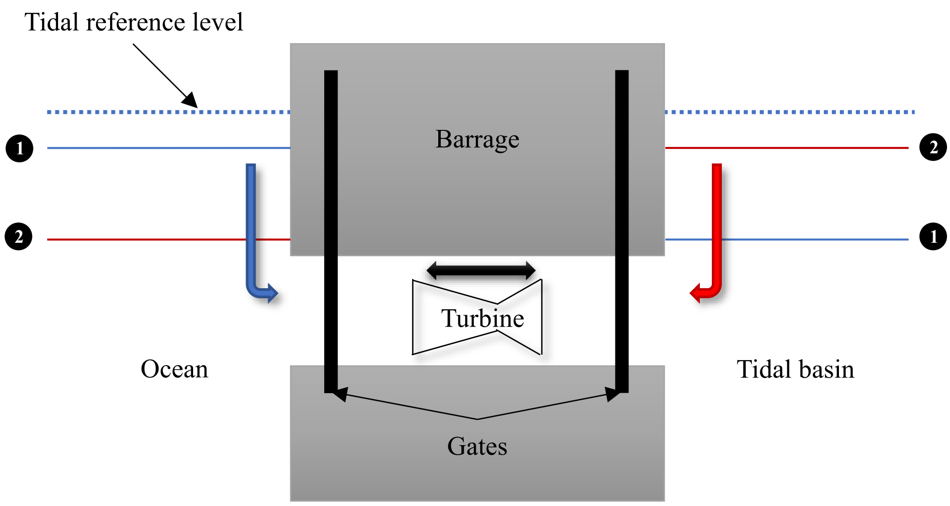


Illustration 20. Tidal power plant cross section view.

In Illustration 20 is shown a typical installation and the bidirectional water flow through the turbine, it is indicated the tidal reference point (blue dashed line) and the first level difference (marked as 1) in this sea level, water flows from ocean to the tidal basin (from left to right), the opposite case is given as well, second level difference (marked as 2) allows water to flow from basin to the ocean (from right to left), this process is cycling along time.

Wave power

For this type of technology, waves are different of tides in the main sense of the aleatory water movement, for tides, gravitational influence between Earth and moon generates the water displacement, in the case of waves there several ways starting from wind currents until considering Coriolis' effect.

Is not a mature technology due to the constant research and improvement of different designs (that are several and variated) to take advantage of the oscillating movement of water, some of them are as follows:

- **Point absorber buoys:** for this type of technology is included a buoy fixed in the seabed to ensure a single point that follows the water surface path, and it transforms into linear movement.

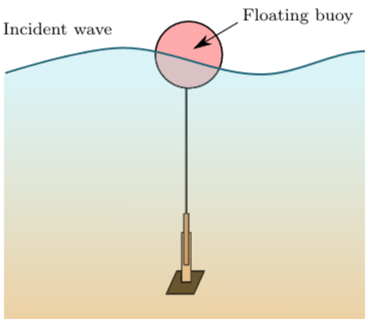


Illustration 21. Representation of a point absorber buoy [17].

- **Surface attenuators:** it operates in parallel to the wave's direction, the structure includes several individual modules interconnected through a flexible mechanism taking advantage of the relative movement.


Illustration 22. Attenuator working concept [18].

- **Oscillating water columns:** this type of technology does not use wave oscillations directly, but the air flow produced by the pressure differences caused by that. In the most basic structure, is needed a pressurized chamber where water increases the internal pressure allowing air to flow towards an axial turbine. In the opposite case, when the water level decreases, a vacuum is generated causing the air flows inside the chamber.

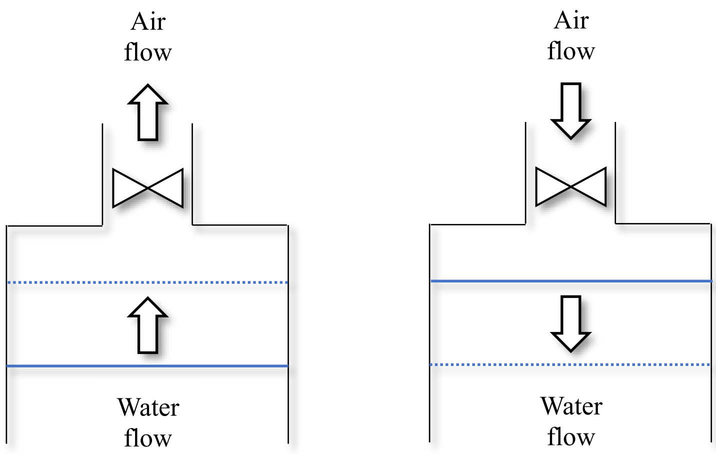


Illustration 23. Scheme of an oscillating water column device.

- **Overtopping devices:** in this type of devices, like the oscillating water devices, a structural design is needed to install a low-head turbine where the captured water that exceeds the overtopping level, flowing inside into a storage reservoir and then goes through a small penstock actioning the turbine.

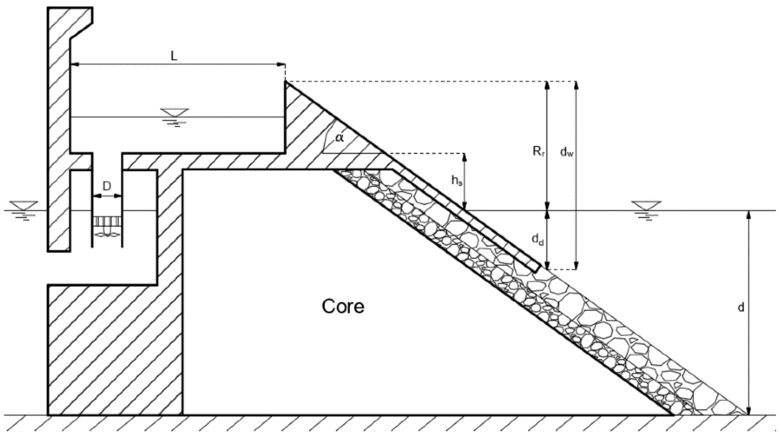


Illustration 24. Cross section of an overtopping device [19].

2.1.7 Wind power

It is the energy source of wind, air flow has several mechanisms involving local influences like temperature differences and global ones that includes Earth's movement and Coriolis's effect, main advantage of this source is similar to solar one and is the virtually inexhaustible fuel but with the inconvenient that is also unpredictable and variable along the time.

Wind turbines are the most spread technologies to take advantage of wind, there are mainly 3 types:

- **Darrieus wind turbine:** this type of turbines is categorized in the vertical-axis family and consists in two or three blades that are joined into a vertical axis, advantage of this kind or turbines are the possibility to operate with good efficiency but the drawbacks associated are the high ripple torque and high stress induced to the axis, for this case is generally coupled another type of turbine to compensate this torque.

Illustration 25. 4 MW Darrieus wind turbine [20].

- **Savonius wind turbine:** it compensates the ripple torque but is limited in power and efficiency that is suitable for remote devices like measurement ones (anemometer is one application).
- **Horizontal wind turbine:** it is the most extended device for onshore and offshore facilities, it consists in a nacelle located in the upper part of a tower that holds a rotor with typically three blades. Inside the nacelle are located several devices of mechanical transformation, electricity generation and control systems.

Wind turbine components

For a horizontal wind turbine, depending on the configuration, electric connection and for each manufacturer design the main components are similar each other, the most general components are detailed as follows:

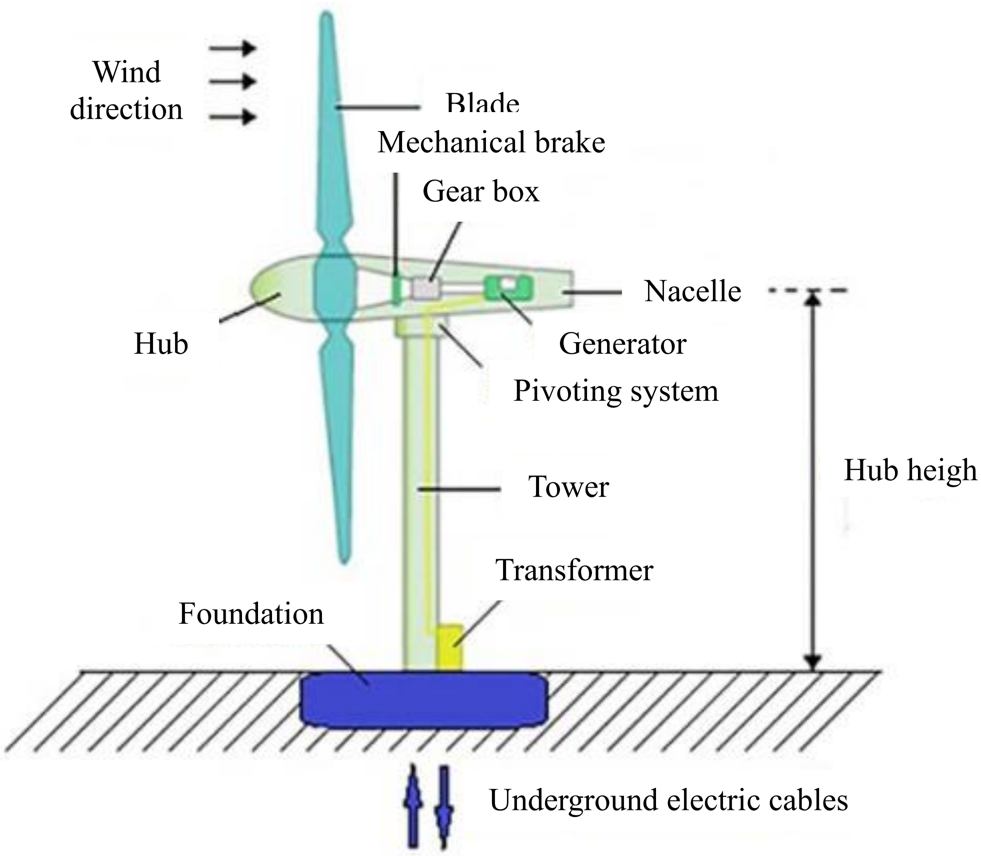


Illustration 26. Overall components of a horizontal wind turbine [21].

- **Foundation:** is the solid base where the tower is installed, it is prepared to endure the flection stresses, vertical weight, and an underground wiring structure is included for interconnection between the turbine and central control room.
- **Tower:** is the most critical structure where all device is supported, inside allows the space for maintenance and cable installation from the generator in the nacelle.
  - **Pivoting system:** or yaw system, it consists of a group of elements that allow the nacelle to orientate towards the wind flow, depending on the design it can be used electric motors or a hydraulic system; a bearing group and a brake system to fix the nacelle in a concrete position.
- **Nacelle:** it is the top structure installed in the upper part of the tower, it offers protection and support of the rest of components.
  - **Gearbox:** it is a mechanical converter that increases the angular velocity of the shift to the generator through diameter gear ratios; it also separates the low and high velocity shifts (related to the hub and generator shifts respectively)

- **Mechanical breaker:** it is a couple of breakers actioned by a hydraulic system to protect over-velocity and avoid an excess of stress in the shift, gearbox, bearings, etc.
- **Generator:** related to the device that converts mechanical energy into electrical one, some generators incorporate several protection and electronic systems regarding to reduce the impact of wind instability nature. It can be a three-phase, single-phase, or direct current connection.

- **Hub:** is the component that supports the blades and inside is installed the pitch control system.
- **Blades:** these are the elements that converts wind energy into mechanical one, the shape profile of each one is designed to be aerodynamic and obtain the maximum amount of energy and allows to offer aerodynamic resistance at certain angles.
- **Transformer:** as the name indicates, is the element in charge of change electricity from one voltage level to another one, depending on the wind turbine design can be incorporated in the nacelle or in the base of the tower.

Wind energy

The objective of a wind turbine is to transform the wind kinetic energy into electrical one. From Navier-Stokes's equations is possible to evaluate all kind of variations in three-dimensional systems, has been formulated several articles to solve this formulation using numerical methods and different approaches, the easiest way to formulate the potential energy available for a wind flow is considering a one-dimensional in steady state conditions.

$$P = \frac{1}{2}\rho A_b v^3 \quad \textbf{Eq. 13}$$

$$P_e = P\eta \quad \textbf{Eq. 14}$$

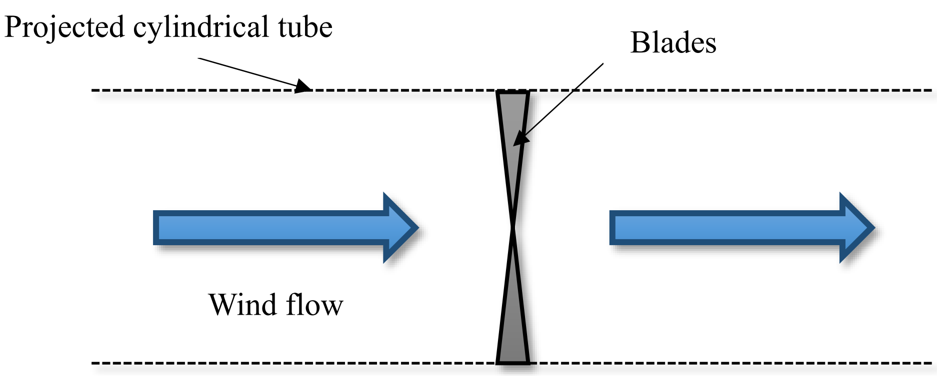


Illustration 27. One-dimensional projected conditions.

Eq. 13 express the relationship between wind flow crossing into a projected cylindrical tube in one dimension (see Illustration 27), it is interesting to notice that the energy obtained depends strongly on the ambient temperature and wind velocity, if temperature increases, density decreases and reduces the amount of energy that can be extracted. In any case, the effect of the velocity is much more relevant in the fact that is a third order relationship. Eq. 14 indicates the electrical output considering all losses through the transformation process.

Wind turbine power profile

Just taking in consideration Eq. 13 is possibly to define that for lower velocities we can obtain big amounts of energy, but considering physical constraints not all energy can be taken advantage and is important due to the highest stresses that materials are exposed at higher velocities, this is why manufacturers elaborates performance curves that defines the regions that a particular wind turbine can operate safety.

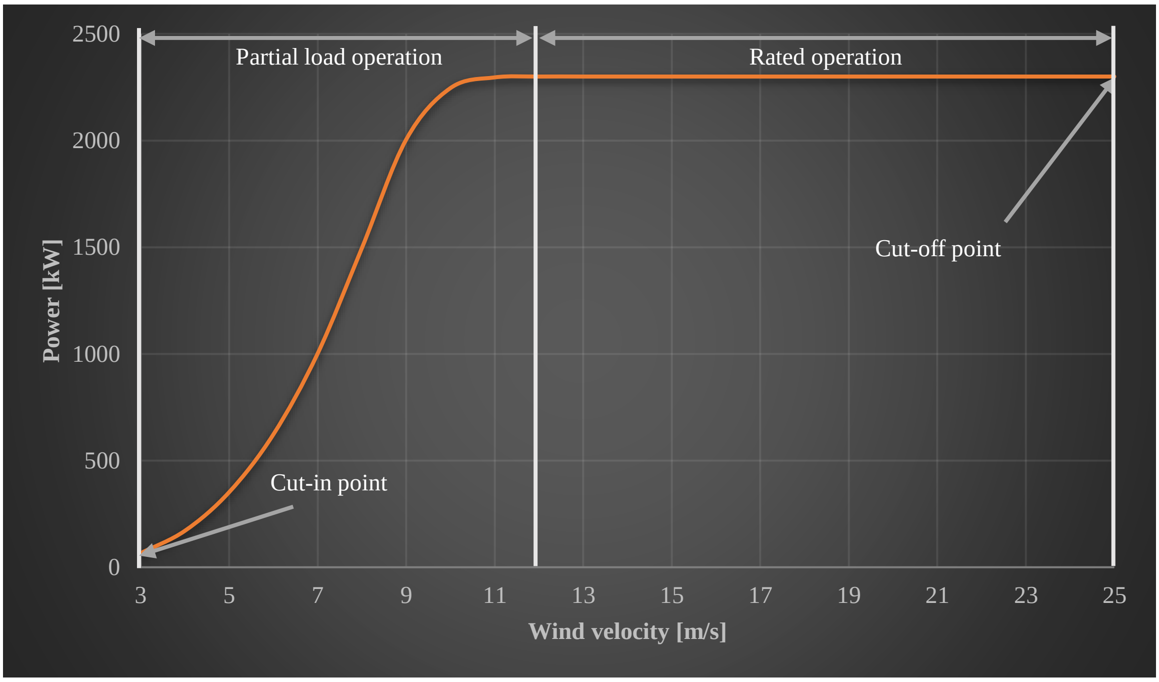


Illustration 28. Typical turbine power curve for a Siemens SWT-2.3-113 model [22].

- **Cut-in point:** it is the minimum wind velocity needed to overcome the different component's inertia and start producing energy from a wind turbine, common values are between 3 – 4 m/s.
- **Partial load operation:** it is a region where the turbine is producing under nominal conditions, it can be limited by wind velocity or by turbine's management system.
- **Rated operation:** it is the range that covers several wind velocities producing the nominal power, in this region, power output is controlled by the management system

through pitch control mainly that reduces aerodynamic performance to ensure a constant power production.

- **Cut-off point:** it is the maximum condition of wind velocity to produce power, over this value the turbine cut any production and brakes are required, typically is set in 25 m/s.
- **Survival velocity:** it is regarded as the ultimate velocity that a turbine can be exposed, over this value it can be permanently damaged requiring corrective actions, common values are around 50 – 60 m/s.

2.2 Non-Renewable energy sources

2.2.1 Conventional power plants

This kind of power plants incorporate all electrical energy facilities that uses fossil fuels (oil, coal, and gas), basically consists of combustion of these fuels to move a generator. There are several ways; from one side, diesel combustion engines use liquid fuel that liberates energy by instant combustion in a chamber, all energy released is transferred to a piston connected to a common shift, this last moves a generator.

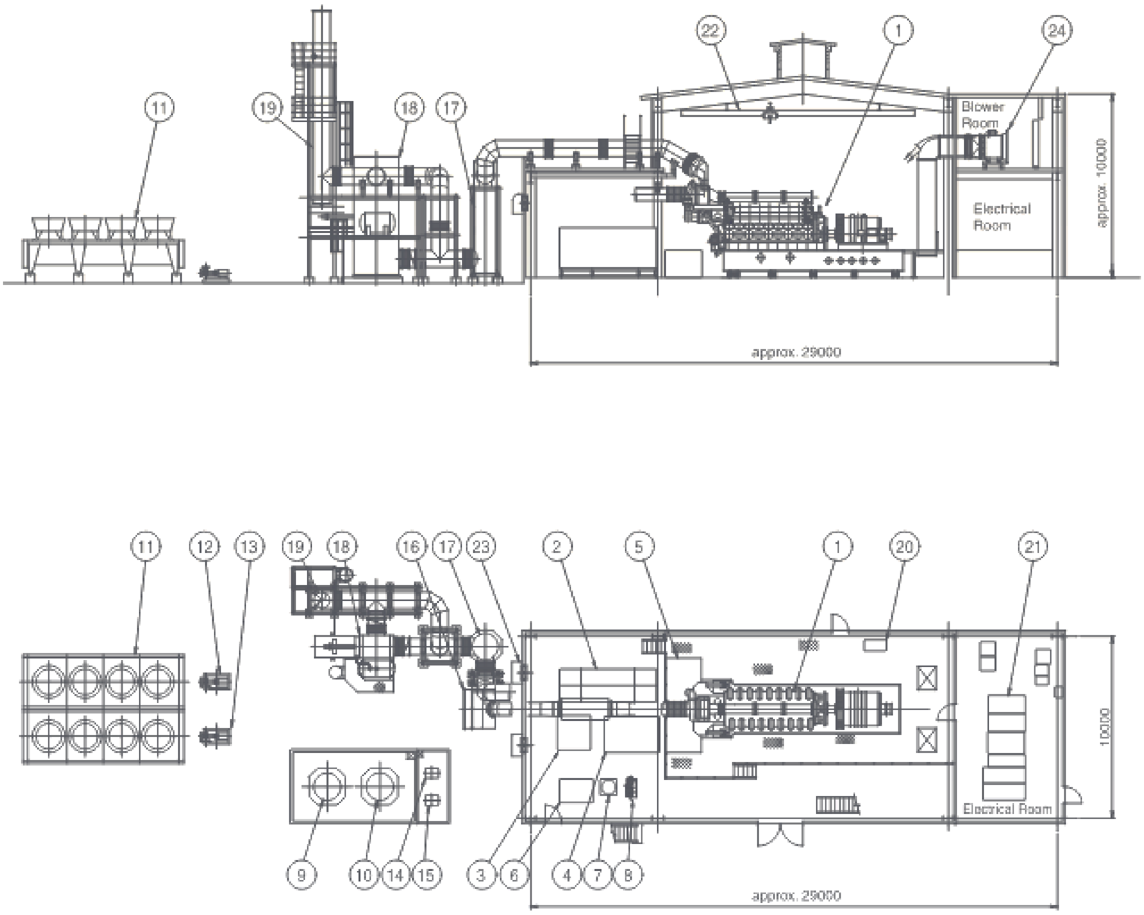


Illustration 29. Example of KU30A engine plant [23].

N°	Item	N°	Item	N°	Item
1	Diesel engine and generator	9	Diesel oil service tank	17	Exhaust gas silencer
2	Lube oil and HT cooling water unit	10	Heavy oil service tank	18	Exhaust gas boiler
3	Lube oil purifier unit	11	Radiator	19	Exhaust gas stack
4	Fuel oil and lube oil filter unit	12	LT cooling water pump	20	Engine gauge board
5	Piping block	13	HT cooling water pump	21	Electrical panels
6	Heavy oil purifier unit	14	Heavy oil supply pump	22	Overhead crane
7	Air receiver	15	Diesel oil supply pump	23	Auxiliary vent fans
8	Air compressor	16	Intake air filter	24	Blowers

Table 4. Example of components in a diesel power plant (regarding to Illustration 29).

By other hand, fuel is used to heat a secondary fluid to move a gas turbine that produces electricity through a generator (see Illustration 30). Heat transfer is given in heat exchangers that separates both the combustion exhaust gases and the thermodynamic fluid (a common fluid is water), and heating until produce overheated vapor.

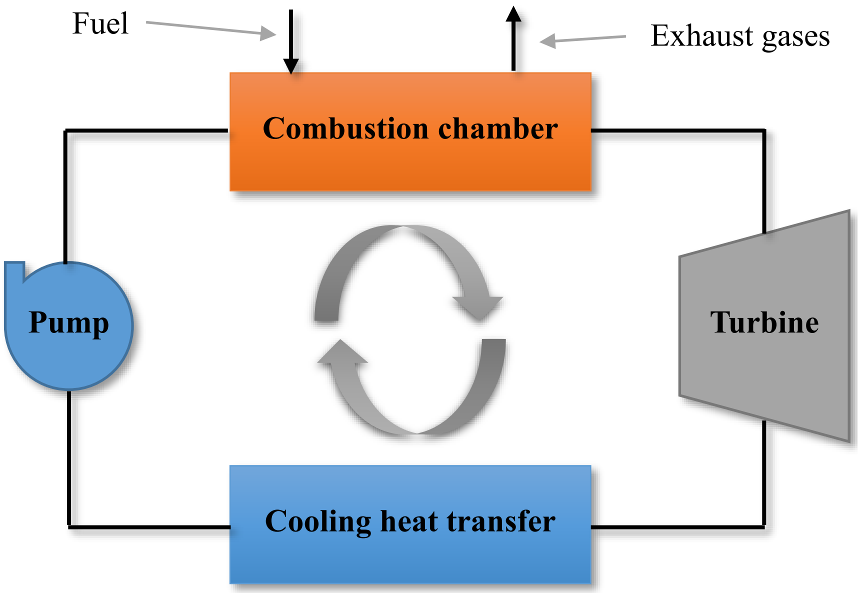


Illustration 30. Representation of a thermodynamic cycle for a conventional power plant scheme.

A variant of this kind of power plant are the cogeneration power plants that incorporate a primary gas cycle (known as Bryton cycle) that are directly used in a turbine to generate electricity, and exhausting gases are incorporated into a boiler to heat a secondary fluid (typically water).

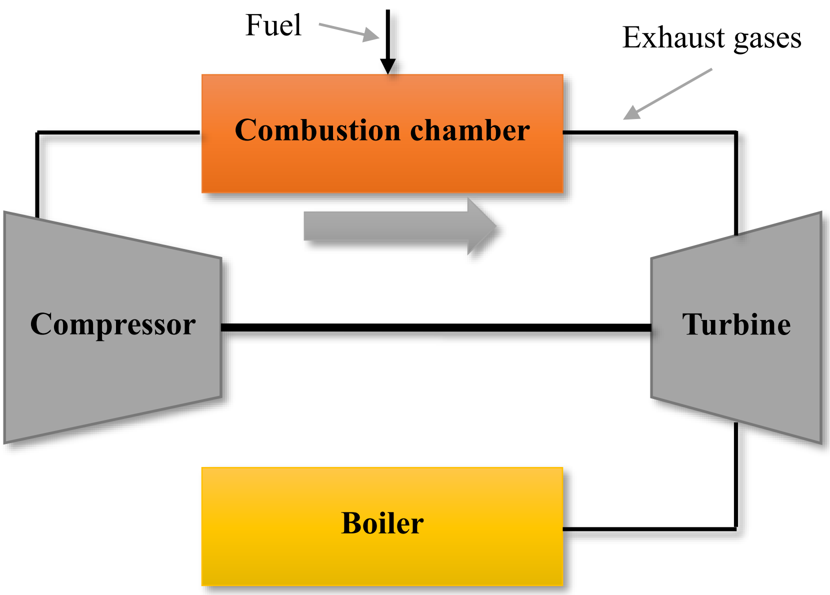


Illustration 31. Representation of a thermodynamic cycle for a cogeneration power plant scheme.

Notice that in Illustration 31 the boiler can be the combustion chamber of Illustration 30 and have electricity production from gas cycle and vapor one making a more efficient system.

Main drawback of these kind of facilities is the issue regarding on environmental regulations according to liberation of greenhouse gases and the limitations of fuel availability, market prices, and logistics related to fuel transport and storage. The advantage of this kind of system is the immediately available power needed for sudden changes in demand that can be adjusted in a short period of time.

2.2.2 Nuclear power

Nuclear power is the type of energy due of atomic reactions like fusion, fission, and atomic decay, the first one results joining two or more atoms to produce other element, the best example of this kind of process is solar energy where hydrogen atoms react to produce helium.

Fission processes is the opposite of fusion, in this case, an element reacts to split their individual components and obtain single atoms. It is needed a heavy element and a charged particle to activate the fission, for a nuclear power plant, the base element is uranium-235. Now to initiate the reaction, a neutron particle is released, when it impacts a uranium core it becomes (momentarily) into uranium-236[17] and split into krypton-92 and barium-141 (both unstable isotopes) releasing neutrons and heat in the process, this last is a decay reaction.

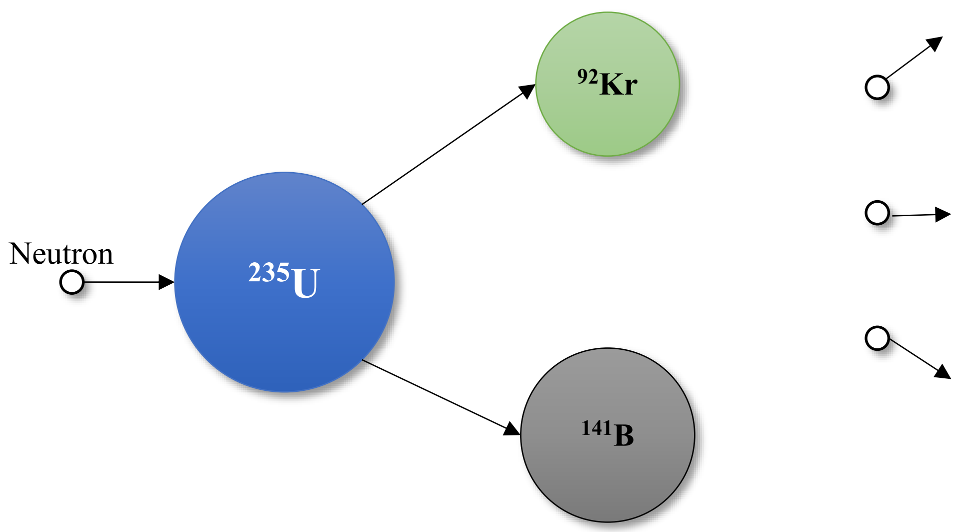


Illustration 32. Fission reaction process.

[17] The neutron incorporates into the core of the atom generating a new unstable isotope.

New neutrons released will collide to other uranium atoms and producing a chain reaction. To avoid an unstoppable reaction, several measures are needed like the reactor design, control rods, and using a coolant moderator.

In a nuclear power plant this kind of reactions are strongly monitored and managed using control rods, those are made of an alloy of Ag-In-Cd (silver, indium, and cadmium respectively), this alloy can absorb a large number of neutrons without suffer nuclear decay itself.

The use a moderator fluid is critical to maintain the correct working conditions to keep reactions under control as the case of deuterium oxide (or heavy water) that reduces the overall velocity reaction through reducing the kinetic energy of free neutrons.

Another function of heavy water is to keep stable the main temperature of the reactor transferring thermal energy to a secondary cooling circuit. A heat transfer device is used to separate both circuits and overheat a fluid that transfers energy to a turbine and produce electricity.

Main advantage of this kind of application is the high energy density of uranium, it is approximately 24 GWh per kg, in contrast, 1 kg of coal has 8 kWh (3 million times more) [24], for this reason, one single rod of fuel can operate continuously during 1 year or 18 months and then replaced to maintain an efficient operational performance.

Disposal of used fuel depends on the policy of each country, but in general there are two main options: recycling the usable part of uranium or permanently storage [25].

2.3 Energetic vector: Hydrogen

2.3.1 Production

Hydrogen production refers to the process of generating hydrogen gas, which is used in a variety of applications, from fuel for vehicles to power plants and chemical manufacturing processes. There are several methods for producing hydrogen gas as follows:

- **Steam Methane Reforming (SMR):** it is the most common method for hydrogen production, accounting for around 95% [26] of global hydrogen production. It involves reacting natural gas (mostly methane) with steam at high temperatures and pressures to produce hydrogen gas and carbon dioxide. The carbon dioxide is then typically captured and stored or used in other applications.
- **Electrolysis:** it refers to split water molecules into hydrogen and oxygen (both in gas phase) through electrical energy for the process. It can be powered by renewable energy sources as previously seen like solar or wind power, making it potentially sustainable method for hydrogen production.
- **Partial oxidation:** hydrogen can be obtained reacting a hydrocarbon fuel (natural gas, gasoline, or diesel) with oxygen to produce hydrogen gas and carbon monoxide. The carbon monoxide[18] can then be reacted with steam in a process called water-gas shift [27] to produce additional hydrogen gas and carbon dioxide.
- **Biomass gasification:** involves heating biomass (wood chips or agricultural waste) in the absence of oxygen to produce a gas mixture known as syngas, which contains hydrogen gas, carbon monoxide, and other gases. Syngas can then be separated and purified to obtain hydrogen.
- **Thermochemical water splitting:** it is related to use heat to break down a metal oxide into oxygen and metal atoms at a relative high efficiency up to 40% [28]. They are then reacted with water to produce hydrogen gas and the metal oxide, which can be reused in the process, in contrast, is a close loop that only consumes water in the process.

In fact, hydrogen does not exist in pure form at nature, but must be extracted from other substances. Once produced, hydrogen can be stored and transported to be used as an energy source in a variety of applications, and for this reason, hydrogen is considered as an energy carrier or vector.

One of the main advantages of hydrogen as an energy carrier is that it can be used in a wide range of applications, from transportation to industrial processes and power generation.

[18] Lack of oxygen produces a high fraction of CO in the process.

In addition, hydrogen can be produced from a variety of feedstocks, including natural gas, biomass, and renewable energy sources. This versatility and flexibility make it an attractive option for meeting a range of energy needs and reducing greenhouse gas emissions.

Moreover, hydrogen has a high energy density by weight, which means that it contains a large amount of energy for its weight, making it a potentially efficient fuel for transportation applications. When it is burned, hydrogen produces only water and heat, making it a clean and environmentally friendly fuel option.

Overall, the versatility, abundance, and clean-burning properties of hydrogen make it a promising energy carrier and it is taking into account by diversification of energetic mix in the future [29]. However, producing, storing, and transporting hydrogen at scale can still be challenging requiring constant research and developments to overcome technical and economic barriers.

2.3.2 Storage

Hydrogen storage is a crucial component. Since it has a low density by volume, it requires significant storage space, which can be a challenge for certain applications such as transportation. Several methods have been implemented as follows:

- **Compressed gas storage:** it can be compressed and stored in high-pressure tanks, typically at pressures between 350 and 700 bar [30]. This method requires tanks that are heavier and larger than conventional fuel tanks, which can limit their use in some applications.
- **Liquid hydrogen storage:** it can be cooled and stored as a liquid at cryogenic temperatures in specialized tanks [31]. This method requires significant insulation to prevent the hydrogen from evaporating and can be expensive and energy intensive.
- **Chemical hydrogen storage:** another way to storage hydrogen is through chemical reaction by combining it with other elements, such as metals or organic compounds [32]. This method can provide high storage densities but requires energy to release the hydrogen, which can limit its efficiency.

- **Material-based storage:** it consists in materials that absorb or adsorb the gas, such as metal hydrides or carbon nanotubes [32]. This method can provide high storage densities and is a reversible process, a drawback of this kind of process is the relative slow time required and high temperatures or pressures needed to release the hydrogen.

2.3.3 Use

Nowadays, hydrogen has several uses in different industries and applications regarding of its inherent advantages, notice that its widespread adoption and utilization face challenges related to production, storage, distribution infrastructure, and costs. However, ongoing research and technical improvements are working to address these challenges and promote the importance of hydrogen in energetic structure as a clean energy source.

Transportation fuel

It can be used as a fuel for vehicles, either in hydrogen fuel cell electric vehicles or in hydrogen internal combustion engine vehicles. It is important to notice that in the case of fuel cells electric vehicles, the use of hydrogen is to generate electricity, which powers the vehicle's electric motor. This kind of application produces zero emissions due the fact that the only by-product is water vapor and heat [33].

Industrial processes

Hydrogen is widely used in industrial applications, particularly in petroleum refining, ammonia production, and methanol production. It is used as a reactant or feedstock in several chemical processes and refining operators [34].

Power generation

This application is regarded as the capacity of hydrogen to generates electricity. It can be directly burned in a turbine or used in fuel cells to produce electricity at high efficiencies and with lower emissions compared to conventional fossil fuels-based power plants [35].

Energy storage

Previously has been discussed the high energy density of hydrogen, this means that a huge amount of energy can be stored in tanks for a prolongated period of time without degradation [36].

An important point to take into account is that hydrogen can be produced by renewable sources like solar and wind power during periods of excess generation and later used for power generation or other applications when renewable energy supply is limited.

Residential and commercial heating

This type of application is regarded for heating residential and commercial buildings. It can be burned for space heating or combined with natural gas in existing natural gas infrastructure [37].

Energy and power backup

Hydrogen can be used as a backup power source for critical systems, such as telecommunications, hospitals, and data centres. It provides a reliable and long-duration energy supply during power outages [38].

Hydrogen fuel stations

Related to mobility applications, hydrogen fuelling stations are being stablished to support the growing number of hydrogen-powered vehicles. These stations provide a refuelling infrastructure for fuel cell electric vehicles, enabling longer-range travel, and promoting the adoption of hydrogen-powered transportation.

2.3.4 Scalability

The scalability of hydrogen production and utilization is an important consideration for its widespread adoption as an energy carrier. While hydrogen holds promises for various applications, there are both opportunities and challenges regarding scalability.

For one side, hydrogen can be produced at various levels, from small scale systems for localized applications to large scale industrial facilities. It depends on the chosen production method and the availability of feedstocks. Steam methane reforming (SMR) is the predominant method [26], is already scaled up and widely used. However, to achieve greater scalability, there is a need to expand production capacity, diversification of sources (such as electrolysis from renewable methods), and optimization of production processes.

Another point to cover hydrogen scalability is the infrastructure needed. This includes the development of a robust hydrogen distribution and storage network, as well as the establishment of hydrogen refuelling stations for transportation applications.

Scaling up infrastructure requires significant investment and coordination among stakeholders, including governments, industries, and energy producers [39].

Costs are another point to consider, as with any technology, achieving scalability often involves cost reductions through economies of scale, advancements in technology, and increased production volumes. The cost of hydrogen production, storage, and transportation is a crucial factor in determining its scalability. Currently, hydrogen production from fossil fuels is more cost-effective compared to renewable energy-powered electrolysis. However, with the declining costs of renewable energy and ongoing research and development efforts, the cost competitiveness of renewable hydrogen is improving as the case of electrolyser technologies aiming to be competitive by 2030 [40].

Supportive policies, regulations, and market mechanisms play a significant role in promoting the scalability of hydrogen. Governments and industry stakeholders are implementing strategies and incentives to foster the growth of hydrogen infrastructure, encourage investment, and stimulate demand for hydrogen-based products [40]. As the market expands and matures, economies of scale can be realized, driving further scalability.

Climate goals are important incentives facilitating international collaboration for impulse hydrogen scalability in several sectors. Cooperation among countries can facilitate knowledge sharing, technology transfer, harmonization of standards, and the establishment of global supply chains for each application and production method. International partnerships and agreements can help accelerate the deployment of hydrogen infrastructure and foster its scalability on a global scale according to diversify the energy production facing actual and future demand without dependence of actual non-renewable sources.

While there are challenges to overcome, such as technology improvements, infrastructure development, and cost reduction, the scalability of hydrogen is feasible and can be accelerated through concerted efforts from industry, governments, and research institutions.

2.4 Environmental European policies

Facing to climate change, the European Union has implemented a number of environmental policies over the years with the aim of protecting the environment and promoting sustainable development, in other words, the EU's environmental policies are designed to promote sustainable development and protect the environment for future generations [41].

One line of action is oriented to reduce greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels and climate neutrality by 2050 [42]. This is supported by several measures such as the EU Emissions Trading System (ETS), which sets a cap on emissions from industry and power plants, and the Effort Sharing Regulation, which sets national emission reduction targets for sectors such as transport, buildings, agriculture, and waste [43].

Another point to consider is the adoption of comprehensive biodiversity strategy for 2030, which aims to protect and restore biodiversity and ecosystems, and to integrate nature into urban areas. This includes measures such as the Natura 2000 network of protected areas [44], and the EU Timber Regulation, which aims to combat illegal logging [45].

Circular economy is an interesting point to take into consideration, where resources are used more efficiently, and waste is minimized. This includes measures such as waste reduction and recycling targets, products design rules, and eco-labelling schemes [46].

For cities, air quality is other sector to be considered stablishing standards to protect human health and environmental surroundings implementing certain measures to reduce air pollution from sources such as industry, transport, and agriculture.

Considering water is an invaluable resource, the quality of it is one of the most important measures to handle stablishing a legal framework to ensure that all bodies of water in EU are in good ecological status by 2027 [47].

3 Dynamic Virtual Power Plant (DVPP)

3.1 Definition

A Dynamic Virtual Power Plant (DVPP) is a concept that combines several distributed energy resources into a single and coordinated system that operates as a unique plant. Unlike traditional power plants that rely on centralized generation facilities, a DVPP harnesses the power of multiple smaller-scale distributed resources, such as solar plants, windmills, energy storage systems (ESS), and even devices connected to the grid (like electric vehicles), to create a flexible and responsive energy network [48].

A DVPP uses advanced software and communication technologies to integrate and control these diverse resources. It enables the aggregation and optimization of their energy generation, consumption, and storage capabilities. By coordinating the operation between generation and demand, the DVPP can mimic the behaviour of a conventional power plant, providing reliable and dispatchable power to the grid.

One key point feature of DVPP is its ability to dynamically adjust the output of each resource based on real-time conditions. It can respond to changes in electricity demand, market prices, and grid conditions, optimizing the overall operation of the virtual power plant [49]. For example, during times of high electricity demand or grid instability, the DVPP can rapidly ramp up the output of each energy producers to provide additional power and grid support.

It also enables the participation of each energy producer in several energy markets, such as wholesale electricity markets, ancillary services markets, or demand response programs. By aggregating the capabilities of multiple distributors, the DVPP can offer more services like energy trading, frequency regulation, peak shaving, or load balancing, potentially generating revenues for the owners and contributing to the overall grid stability [49]. Benefits of a DVPP can be numerous that include:

- **Grid flexibility and stability:** aggregating and coordinating diverse energy resources, it can enhance reliability, improving power quality, and supports the integration of intermittent renewable energy sources like solar energy and wind power.

- **Costs optimization:** due for its nature, each element of the grid is evaluated in base of the cost of the electricity and maximizing the revenue for each owner taking special consideration in the fluctuation of market prices [48].
- **Energy efficiency:** optimizing the operation of each producer and enabling demand response capabilities, a DVPP can improve the overall energy efficiency by reducing peak demand and using energy resources in a more efficient way.
- **Decentralization and resilience:** another inherent benefit is the resilience facing disruptions, when a producer is not able to provide electricity to the grid, others can afford the deficit to compensate and maintain the overall power supply.

It is interesting to note that a DVPP represents an innovative approach to manage energy distribution in an interconnected grid, leveraging the potential of distributed energy resources and allowing an advanced control system to create a more flexible, efficient, reliable, and sustainable power grid.

3.2 Ancillary services: Frequency and voltage

Both, frequency, and voltage control, play a crucial role in maintaining the stability and reliability of the grid. These services are necessary to ensure that the supply of electricity matches the demand and allowing the grid to operate within acceptable parameters.

Both frequency and voltage control are traditionally provided by large, centralized power plants due to its inherent high-power control. However, with the increasing integration of renewable energy sources and distributed energy resources, the role of ancillary services is evolving [50]. For a DVPP, the diversity of resources and the addition of several variables like ancillary services distributed in a defined geographic grid means a big challenge facing the grid control. It can be achieved by aggregating and coordinating the capabilities of several producers. For example, energy storage systems within a DVPP can respond quickly to frequency deviations by either injecting or absorbing power into the grid [51]. Similarly, voltage control can be achieved by adjusting the reactive power output of each supplier. In fact, a DVPP can hold a grid not only managing the production but also the consumption of power from grid for each supplier (a traditional point of view has been taking the producer’s duty to supply energy only).

By leveraging the flexibility and responsiveness of a supplier through advanced control systems and communication technologies, DVPPs have the potential to provide ancillary services more efficiently and cost-effectively. These services are essential for maintaining the grid stability and accommodating the increasing penetration of renewable energy sources in modern power systems.

3.2.1 Frequency control

It contributes to ensure that the overall frequency of the grid remains within a specific range that depending on the region it can be 50 or 60 Hz[19] by balancing the generation and consumption of electricity. Ancillary services like this help to match the supply and demand by continuously adjusting the generation output. When the demand exceeds supply, the frequency decreases, and vice versa. Automatic Generation Control (AGC) systems and technologies like demand response or energy storage can provide frequency control services [50].

In an interconnected power grid, the balance between electricity generation and consumption must be always maintained at certain limits. Any deviation in this balance can cause the frequency deviation from nominal values, in order of reaction, several control measures are given.

- **Load-Frequency Control (LFC):** also known as Automatic Generation Control (AGS), is the primary mechanism for maintaining frequency within normal range. It continuously adjusts the generation output to match the electricity demand in real-time. It relies on communication between power plants and the grid operator to monitor the grid's frequency and make necessary adjustments [52]. When the frequency suffers any difference, the supplier reacts in two scenarios. If the frequency is too high, generation is reduced, and if the frequency is too low, generation is increased.

[19] In American continent, power frequency is mainly in 60 Hz, the rest of the world is 50 Hz predominant frequency. Japan's electric grid is particular due it works in both frequencies dividing it in two regions.

- **Primary frequency response:** this is regarded to the inherent inertia mass response for generators the conventional power plants (it can be included flywheels as an example of inertial elements added into a power plant) [53]. When a sudden increase in demand or a loss of generation is detected, the rotational inertia of these generators helps to slow down the frequency decline. Similarly, when there is an excess of generation, the rotational inertia assists in slowing down the frequency rise.
- **Secondary frequency response:** it provides additional support to primary frequency control. It involves the active participation of additional elements, such as fast-acting reserves, energy storage systems, and demand response. These resources can quickly inject or absorb power to help the stabilization of the frequency when there are sudden disturbances. If the case of frequency drops, ESSs or demand response programs can inject power into the grid to support frequency recovery [54].

Not only sudden changes in demand can affect frequency values, but also sudden changes in energy generation can contribute to modify overall grid's stability. The case of renewable energies is scenario where the production can drop suddenly due to climatic conditions, for this reason, the increasing integration of renewable energy sources, frequency control becomes more challenging due this randomly behaviour. However, it also presents new opportunities. For example, allowing a high-level control algorithm, a renewable resource can participate in frequency control markets like solar production through smart inverters providing frequency support by dynamically adjusting their power output based on frequency deviation.

3.2.2 Voltage control

This service is essential to maintain the voltage level within acceptable ranges throughout the grid. Fluctuations in voltage affect the performance and lifespan of electrical equipment and appliances. Ancillary services for voltage control involve the regulation of potential level in several points of the grid to ensure the stability and keeping the same potential in the grid [55]. Voltage can be controlled through various means, including transformers, voltage regulators, capacitors, and reactive power compensation devices.

Inside of a DVPP, voltage control can be achieved by coordinating the operation of distributed energy resources in a similar way as that it does with frequency control allowing to generate or absorb power from grid and using electronic energy conversion to manage the voltage disturbs. There are several methods to achieve this goal.

- **Voltage regulation:** it involves the adjustment of voltage at various points in the grid to maintain it within specified limits. Voltage regulators and transformers are commonly used to it [55]. By one hand, voltage regulators can adjust the transformer tap settings to increase or decrease the voltage, by other hand, transformers can step up or step down the voltage as required.
- **Reactive power control:** AC signals have reactive components that can be modified in order to modify the real voltage needed in the grid. Reactive devices such as capacitors and reactors (or referred as inductors) are employed to inject or absorb reactive power at specific locations to regulate voltage levels [56]. Capacitors can also provide reactive power support by supplying leading reactive power, while reactors can absorb reactive power, providing lagging reactive signals.
- **Power factor correction:** it is well known that the power factor is the ratio between active and apparent power in AC system. For producer devices like inverters, the electronic associated can adjusts it output power factor at a desired level (typically close to unity) [57].

4 Geographic delimitation

Delimiting a geographic region to develop a DVPP involves considering several boundaries within which supplier will be aggregated and coordinated, in the context of performing a DVPP and the algorithm associated can be considered several considerations in the physical region.

Firstly, Catalonia has been chosen due to the facility of gather reliable and updated information from local organisms regarding to physical structure, regulatory boundaries, grid network structure, resources availability, and some markets considerations.

It is important to note that the delimitation responds a strategic decision that requires some general technical considerations, computational power, and operational factors. In real operation, some considerations are taken like power line losses, harmonic deviations, reactive power injected to the grid, and temperature effects in the material's properties.

Selection of a specific region allows to consider the actual potential resources, for the evaluation in Catalonia, has been selected three types of renewable energy: photovoltaic solar energy, onshore wind power, and offshore wind power since is possible to gather potential resources data from websites such as Nasa website, Renewables.ninja, and PVGIS.

N°	Source	Location	Coordinates
1	Photovoltaic	Agramut	41°45'55" N, 0°59'39" E
2		Alguaire	41°44'19" N, 0°30'14" E
3		Bellcaire d'Urgell	41°44'59" N, 0°51'39" E
4		Gimerà	41°32'49" N, 1°11'41" E
5		Juneda	41°32'45" N, 0°47'9" E
6		Maials	41°21'37" N, 0°29'30" E
7	Onshore wind power	Corbera d'Ebre	41°7'44" N, 0°27'2" E
8		Josa Tuixent	42°16'38" N, 1°39'32" E
9		La Jonquera	42°26'36" N, 2°53'56" E
10		Paüls	40°57'29" N, 0°24'32" E
11		Roses	42°16'42" N, 3°14'17" E
12		Tarragona	41°19'27" N, 1°1'9" E
13	Offshore wind power	Gulf of Roses	42°8'51" N, 3°20'9" E
14		L'Amtella de Mar	40°51'39" N, 1°13'55" E
15		L'Startit	42°1'25" N, 3°39'21" E
16		Sant Feliu de Guíxols	41°39'53" N, 3°51'32" E

Table 5. Location of the selected places for new power plants.

4.1 Demand

To define the baseline to start the analysis of the optimization model, the demand data is needed, this information is obtained from Catalonia's Transparency Portal website[20]. The information required is in first place an annual record of hourly demand for each day, the starting year for this simulation is taken from 2020.

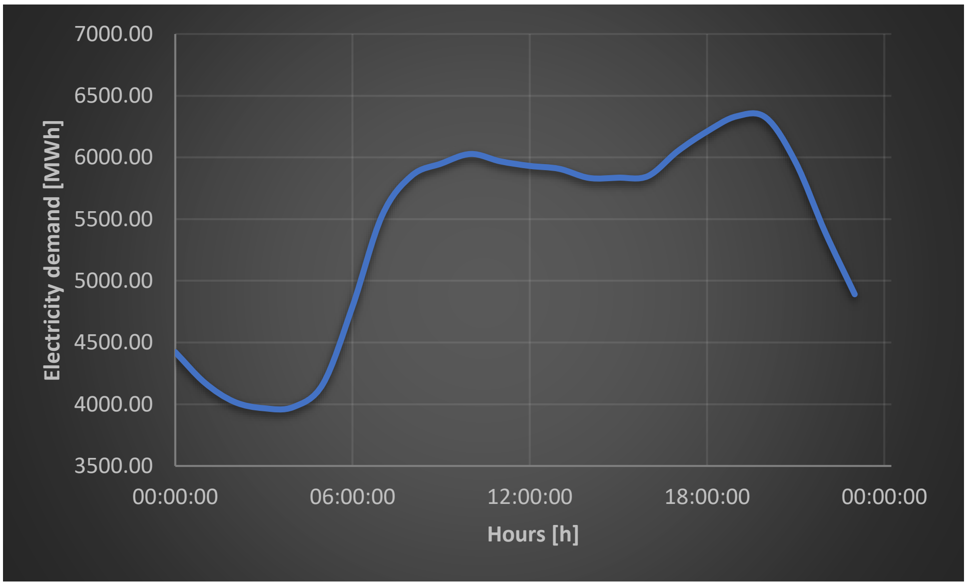


Illustration 33. Typical-day demand profile per hour. Data is courtesy of Catalonia's Transparency Portal.

Illustration 33 indicates the usual behaviour of electricity demand in Catalonia, it can be differentiating different hourly segments depending on electricity consumption that can vary depending on several factors such as geographic location, climate, cultural practices, holidays, and mix-share between commercial, households, and industrial activities.

- **Early morning:** it is the time gap between midnight and 6:00 in which the demand is the lowest due to most people are asleep, residential consumption is minimum, and the basic electrical devices are connected.
- **Morning peak:** it is considered from 6:00 to 9:00, electricity demand increases due people wake up and uses appliances, at this period, in commercial and industrial activities as businesses open and employees start workday.
- **Midday to afternoon:** currently, the consumption is relatively constant or steady due to the normal activity during day.

[20] https://analisi.transparenciacatalunya.cat/

- **Afternoon decrease:** it can vary from 16:00 to 17:00 to 20:00 hours, where the demand tends to experience a slight drop during some people leave work, but some household appliances are used for cooking, lighting, and entertainment.
- **Evening peak:** usually is the time between 20:00 to 22:00 when all people return from work, residential consumption increases significantly, and commercial activities contribute as well, at this time can be reached the highest consumption depending on the year season and region.
- **Late evening:** from 22:00 to midnight is the time when the consumption decreases significantly due people prepare for sleep.

4.2 Recent renewables and nuclear installed capacity

Regarding to the installed capacity in Catalonia, from REE database[21], until 2022 has been reported a power capacity of 11963 MW between renewable and non-renewable plants.

N°	Source	Installed capacity [MW]
1	Hydropower	1922
2	Pumped storage hydropower	440
3	Photovoltaic	296
4	Renewable waste	27
5	Solar thermal	24
6	Wind power	1369
7	Other renewables	64
8	Nuclear	3033
	Total renewables	**4142**

Table 6. Installed capacity for renewable and nuclear sources for 2022. Data courtesy by REE.

Notice that neglecting the rest of non-renewable sources, nuclear power is the largest single source installed in Catalonia[22], the case of renewable sources the power installed capacity represent a global share 34.62% approximately more than one third of the total capacity where hydroelectric facilities represent 16% making the biggest technology followed by windmill facilities (11.44% share).

[21] https://www.ree.es/es/datos/generacion/potencia-instalada
[22] The largest single source installed is combined cycle facilities with 3788 MW until 2022.

5 Methodology

5.1 Optimization method: Levelized Cost of Energy

Levelized Cost of Energy (LCOE) is a metric that will be used to compare different scenarios and chose the most appropriate to the global model, it consists of the present cost of generating electricity from different sources. In general terms, it refers into an average present cost per unit of electricity produced over the project lifetime considering most representative costs such as development, construction, operation, maintenance, and fuel costs[23].

Present value of money is indicated for the discount rate, that represents the rate of return or interest rate used to represent the costs and benefits from future projected in present time. Typical values for energy project the range values can vary from 3% to 10% [58].

$$LCOE = \frac{CAPEX + \dfrac{OPEX + RC + FC}{(1+i)^t}}{\dfrac{E_t}{(1+i)^t}} \qquad \textbf{Eq. 15}$$

Where CAPEX are the capital or initial expenditures in the present, operative expenditures, replacement, and fuel costs (OPEX, RC, and FC respectively) indicates costs after the present year until project finalization, if the lifespan of project is the same for the installation RC is neglected. Energy produced each year E_t is transferred at present as well using the discount rate i.

Units used will be Euros per kilowatt-hour (kWh), this last is an energy unit used to quantify the amount of power consumed or produced per each operative hour. Considering costs depends on several factors and the main scope of the analysis, according to the objective of the project, costs of installation, operation, and fuel (if is applicable) are considered.

[23] For renewable sources like PV and wind power, fuel is available in nature and free to use it.

5.2 System modelling

5.2.1 Elements included and constraints included in the model

Nuclear power

It is considered that all energy needed for the grid will be the nominal output all time, taking into consideration the actual power capacity will be the only one used and is not needed to incorporate new nuclear facilities. Nuclear production mathematical model considers a constant production as a baseline energy source.

$$(x_{Nu})_{[t][i]} = P_{Nu[t][i]} \ \forall i, \forall t \qquad \textbf{Eq. 16}$$

The previous equation indicates the specific power used for each nuclear plant at a specific time gap.

Hydropower

Some facilities, due its characteristics, are not able to pump water to the reservoir, these are naturally recharged. Instant production is defined as follows:

$$(x_{HP})_{[t][i]} \leq P_{HP[t][i]} \ \forall i, \forall t \qquad \textbf{Eq. 17}$$

Where x_{HP} is the instant power supplied during in a time t for each hydropower facility i. Notice that at any moment the maximum power generated must be less or equal to the installed capacity.

By other hand, maximum difference power production allowed between two intervals in a row is given by:

$$\left|(x_{HP})_{[t+1][i]} - (x_{HP})_{[t][i]}\right| \leq \Delta P_{HP[i]} \ \forall i, \forall t \qquad \textbf{Eq. 18}$$

In this scenario, maximum difference between intervals must not be greater than the capacity variation given for the same interval.

Pumped storage hydropower

This type of power plant includes all hydropower plants that are allowed with a pumping system to storage energy surplus from grid in the reservoir, it is important to consider two working schemes: grid injection (reservoir discharge) and grid absorption (reservoir charge), for both cases the constraints are given by:

$$[(x_{HP})_{Dis}]_{[t][i]} \leq P_{T[t][i]} \ \forall i, \forall t \qquad \textbf{Eq. 19}$$

$$[(x_{HP})_{Char}]_{[t][i]} \leq P_{P[t][i]} \ \forall i, \forall t \qquad \textbf{Eq. 20}$$

Where $(x_{HP})_{Dis}$ and $(x_{HP})_{Char}$ are the instant power generated and absorbed respectively for a given time t and for each facility i. It is important to notice that installed power for turbines P_T is not compulsory to be the same as the pumping one P_P.

Like previous cases, maximum power production difference between time gaps is given for each condition (charging and discharging).

$$\left|[(x_{HP})_{Dis}]_{[t+1][i]} - [(x_{HP})_{Dis}]_{[t][i]}\right| \leq \Delta P_{T[i]} \ \forall i, \forall t \qquad \textbf{Eq. 21}$$

$$\left|[(x_{HP})_{Char}]_{[t+1][i]} - [(x_{HP})_{Char}]_{[t][i]}\right| \leq \Delta P_{P[i]} \ \forall i, \forall t \qquad \textbf{Eq. 22}$$

Previous equations indicate the maximum power difference between intervals, both generation and absorption must be less or equal to the capacity variation for turbines and pumps respectively.

At this point, it is necessary to evaluate the amount of energy in the reservoir, for this reason, an energy balance must be performed to quantify the net energy stored.

$$E_{Res} = E_{Res[t-1][i]} + E_{Char[t][i]} - E_{Dis[t][i]} \ \ \forall i, \forall t \qquad \textbf{Eq. 23}$$

Note that for performing the energy balance, the previous instant condition is needed, and depending on the hydropower facility infrastructure, some of them are allowed to work in charge and discharge simultaneously. For the development of the model, it is just considered one of both scenarios (charging or discharging but not both at the same time).

$$(E_{Res})_{min} \leq E_{Res} \leq (E_{Res})_{max} \qquad \textbf{Eq. 24}$$

$$(x_{HP})_{Dis} = \frac{E_{Dis}}{t} \qquad \textbf{Eq. 25}$$

$$(x_{HP})_{Char} = \frac{E_{Char}}{t} \qquad \textbf{Eq. 26}$$

Eq. 24 represents the state of charge of the reservoirs, which indicates the amount of energy stored in the dams. This value is limited to the maximum energy capacity of all the dams considered in the system. In other words, it ensures that the state of charge does not exceed the total energy storage capacity available in the reservoirs.

Eq. 25 and Eq. 26 stablish the relationship between power and energy. In the context of the model, the time interval considered for evaluations is 1 hour, which makes power and energy equivalent. This means that the power generated or absorbed by the system in a given hour is equivalent to the energy produced or consumed during that same hour.

These equations help to establish the constraints and relationships between energy storage and power generation/absorption in the model, ensuring that the system operates within the specified limits and considers the available energy resources.

Photovoltaic and wind power (onshore and offshore)

It is considered the case that actual plants and new ones are producing directly to the grid without possibility of an intermediate storage of energy such as batteries, super capacitors, and flywheels. As a result, the production is directly linked to the availability of the source at that moment (it varies randomly along time). Maximum production instant production is defined for both technologies, as follows:

$$(x_{PV})_{[t][i]} \leq P_{PV[t][i]} \; \forall i, \forall t \qquad \textbf{Eq. 27}$$

$$(x_{WP})_{[t][i]} \leq P_{WP[t][i]} \; \forall i, \forall t \qquad \textbf{Eq. 28}$$

Where x_{PV} and x_{WP} are the instant power generation for solar and wind sources respectively for a given time t for each plant i. Production is restricted also for the maximum difference between intervals:

$$\left|(x_{PV})_{[t+1][i]} - (x_{PV})_{[t][i]}\right| \leq \Delta P_{PV[i]} \; \forall i, \forall t \qquad \textbf{Eq. 29}$$

$$\left|(x_{WP})_{[t+1][i]} - (x_{WP})_{[t][i]}\right| \leq \Delta P_{WP[i]} \; \forall i, \forall t \qquad \textbf{Eq. 30}$$

For the previous case, maximum difference for both, photovoltaic and wind power, must not exceed the capacity variation given for the same interval.

Hydrogen facilities

In the case of hydrogen facilities, their behaviour in the model is simplified and treated similarly to a battery system.

The instantaneous power delivered by the hydrogen facilities is defined as the power provided or absorbed from the grid. This value is always less than the maximum power capacity of the electrolyser (for hydrogen production) and the hydrogen fuel cell (for electricity production).

$$\left[\left(x_{Hy}\right)_{Ab}\right]_{[t][i]} \leq P_{El[t][i]}\ \forall i, \forall t \quad \textbf{Eq. 31}$$

$$\left[\left(x_{Hy}\right)_{Gen}\right]_{[t][i]} \leq P_{HFC[t][i]}\ \forall i, \forall t \quad \textbf{Eq. 32}$$

Similar to other cases, there is a constraint on the maximum power production difference between time intervals for each condition. This constraint ensures that the power production or consumption by the hydrogen facilities does not exceed the specified capacity variation for a given time interval.

$$\left|\left[\left(x_{Hy}\right)_{Ab}\right]_{[t+1][i]} - \left[\left(x_{Hy}\right)_{Ab}\right]_{[t][i]}\right| \leq \Delta P_{El[i]}\ \forall i, \forall t \quad \textbf{Eq. 33}$$

$$\left|\left[\left(x_{Hy}\right)_{Gen}\right]_{[t+1][i]} - \left[\left(x_{Hy}\right)_{Gen}\right]_{[t][i]}\right| \leq \Delta P_{HFC[i]}\ \forall i, \forall t \quad \textbf{Eq. 34}$$

At this point, it is necessary to evaluate the amount of energy stored in tanks, for this reason, an energy balance must be performed to quantify the net energy stored.

$$E_{Tank} = E_{Tank[t-1][i]} + E_{Ab[t][i]} - E_{Gen[t][i]}\ \ \forall i, \forall t \quad \textbf{Eq. 35}$$

Note that for performing the energy balance, the previous instant condition is needed, and depending on the facility infrastructure, some of them are allowed to work in charge and discharge simultaneously. For the development of the model, it is just considered one of both scenarios (charging or discharging but not both at the same time).

$$(E_{Tank})_{min} \leq E_{Tank} \leq (E_{Tank})_{max} \quad \textbf{Eq. 36}$$

$$\left(x_{Hy}\right)_{Gen} = \frac{E_{Gen}}{t} \quad \textbf{Eq. 37}$$

$$\left(x_{Hy}\right)_{Ab} = \frac{E_{Ab}}{t} \quad \textbf{Eq. 38}$$

Eq. 36 represents the state of charge of the tank, which indicates how much energy is stored at a given time. This is limited to the maximum amount of energy that can be stored in all the tanks considered in the system.

Eq. 37 and Eq. 38 define the relationship between energy and power. In the context of the model, the time interval for evaluation is set to 1 hour, which means that the power and energy values are considered equivalent within this time interval. This simplification allows for a tractable model and ensures that the energy balance is properly accounted for within each hourly time step. However, it is essential to keep in mind that this simplification might not fully capture the dynamic behaviour of the system in shorter timeframes.

In summary, Eq. 36 ensures that the energy stored in the tank does not exceed its maximum capacity, while Eq. 37 and Eq. 38 relate the energy and power values for an hourly time step, enabling the model to perform energy balancing calculations effectively.

By considering these constraints and modelling the hydrogen facilities in a manner similar to battery systems, the model can effectively represent the behaviour of the hydrogen facilities in the overall energy system optimization.

Energy balance

In the model, each time gap is evaluated individually, performing an energy balance considering all energy demanded, generated, and absorbed (for producing hydrogen), in fact, is considered that demand varies and the contribution of each element in the system must adapt.

$$G_{e[t]} = D_{[t]} + \sum_{i=1}^{n} [(x_{HP})_{Char}]_{[t][i]} + \sum_{i=1}^{n} \left[(x_{Hy})_{Ab} \right]_{[t][i]} \quad \forall i, \forall t \qquad \textbf{Eq. 39}$$

$$G_{e[t]} = \sum_{i=1}^{n} (x_{Nu})_{[t][i]} + \sum_{i=1}^{n} (x_{HP})_{[t][i]} + \sum_{i=1}^{n} [(x_{HP})_{Dis}]_{[t][i]} + \sum_{i=1}^{n} (x_{PV})_{[t][i]} + \sum_{i=1}^{n} (x_{WP})_{[t][i]} + \sum_{i=1}^{n} \left[(x_{Hy})_{Gen} \right]_{[t][i]} \qquad \textbf{Eq. 40}$$

Cost definition

From producers, all costs are represented in CAPEX and OPEX that are the capital expenses and operative and maintenance expenses for each technology, in the context of the model, these costs are expressed as follows:

$$CAPEX_{Ren} = \sum_{i=1}^{n} P_{HP[i]} \cdot CAPEX_{HP} + \sum_{i=1}^{n} P_{T[i]} \cdot CAPEX_{T} + \sum_{i=1}^{n} P_{P[i]} \cdot CAPEX_{P} + \sum_{i=1}^{n} P_{PV[i]} \cdot CAPEX_{PV} + \sum_{i=1}^{n} P_{WP[i]} \cdot CAPEX_{WP} + \sum_{i=1}^{n} P_{El[i]} \cdot CAPEX_{El} + \sum_{i=1}^{n} P_{HFC[i]} \cdot CAPEX_{HFC} \quad \textbf{Eq. 41}$$

$$CAPEX_{Non-Ren} = \sum_{i=1}^{n} P_{Nu[i]} \cdot CAPEX_{Nu} \quad \textbf{Eq. 42}$$

$$OPEX_{Ren} = \sum_{t=1}^{t}\sum_{i=1}^{n} (x_{HP})_{[t][i]} \cdot OPEX_{HP} + \sum_{t=1}^{t}\sum_{i=1}^{n} [(x_{HP})_{Dis}]_{[t][i]} \cdot OPEX_{T} + \sum_{t=1}^{t}\sum_{i=1}^{n} [(x_{HP})_{Char}]_{[t][i]} \cdot OPEX_{P} + \sum_{t=1}^{t}\sum_{i=1}^{n} (x_{PV})_{[t][i]} \cdot OPEX_{PV} + \sum_{t=1}^{t}\sum_{i=1}^{n} (x_{WP})_{[t][i]} \cdot OPEX_{WP} + \sum_{t=1}^{t}\sum_{i=1}^{n} \left[\left(x_{Hy}\right)_{Ab}\right]_{[t][i]} \cdot OPEX_{El} + \sum_{t=1}^{t}\sum_{i=1}^{n} \left[\left(x_{Hy}\right)_{Gen}\right]_{[t][i]} \cdot OPEX_{HFC} \quad \textbf{Eq. 43}$$

$$OPEX_{Non-Ren} = \sum_{t=1}^{t}\sum_{i=1}^{n} (x_{Nu})_{[t][i]} \cdot OPEX_{Nu} \quad \textbf{Eq. 44}$$

Objective function

Optimization method will look for the minimum cost of all available resources per energy produced and absorb, therefore, the objective function will evaluate the CAPEX and OPEX using the LCOE to compare different alternatives and choose the best scenario.

$$\min_{x \in \mathbb{R}} f(x) = LCOE_{Ren} + LCOE_{Non-Ren} \quad \textbf{Eq. 45}$$

5.2.2 General considerations

For modelling the DPPV, some considerations have been taken to simplify and represent an overall behaviour to elaborate the best solution under the actual scheme. The following assumptions help to create a tractable model that can be used as a reference to improve and increase the accuracy of the grid network.

- **Producers:** energy dispatchability is instantaneous and response times are negligible. Power plant size is unlimited for all renewable sources, and the behaviour per hour is only limited by local environmental conditions. In the case of nuclear power plants, the installed capacity is the present one avoiding to increasing along time.
- **Aggregation:** all producers are perfectly coordinated facing energy demand allowing the plant production for the producer with better conditions in terms of LCOE (considering constant discount rates). Distance between distributed producers does not affect the performance of the grid and grid losses are negligible.
- **Market dynamic:** for this model, energy prices are not considered, instead, the levelized cost of energy has been taken into account to sizing DPPV.
- **Forecasting:** to evaluate the system demand, base data have been selected from national database for the year 2022 with a projected lifetime of 50 years.
- **Operational constraints:** to simplify the model and reduce the computational power, ramp rates and minimum on/off times are not considered, instead energy storage limitations are stablished. Also, the efficiency reduction is negligible allowing to produce at nominal conditions when is required.
- **Grid dynamics:** transient elements in the grid are neglected such as harmonics, parasite losses in the grid, and reactive power injected to the grid allowing the grid to operate in steady state conditions all time.

5.3 Optimization problem

5.3.1 Case 1

In the first model, the base case scenario is considered, where the energy system consists of multiple producers with a relatively low renewable energy share. This includes the presence of nuclear power plants and gas-operated plants, along with a 35% share of renewable energy sources such as photovoltaics and wind power.

The model aims to optimize the energy system by determining the optimal mix of energy generation from these sources while considering the constraints and objectives of the system. The goal is to minimize the overall cost, taking into account the levelized cost of energy (LCOE) and the specific costs associated with each technology, including capital expenditures (CAPEX) and operational expenses (OPEX).

N°	Source	Installed capacity [MW]	Capacity factor	LCOE [€/kWh]
1	Nuclear	2641	100%	0.038
2	Gas	3679	15.02%	0.175
3	Photovoltaics	3151	17.80%	0.035
4	Wind power	3870	29.40%	0.035
	Total	**13341.26**		**0.056**

Table 7. Installed capacity, capacity factor, and LCOE for the base case.

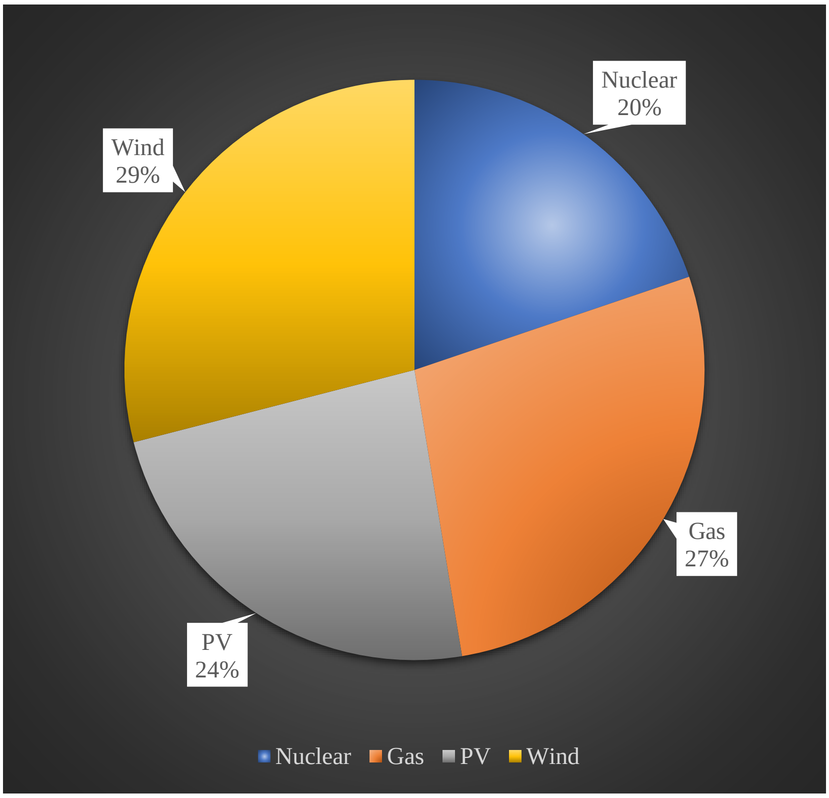


Illustration 34. Composition at 35% of renewable share for the base case.

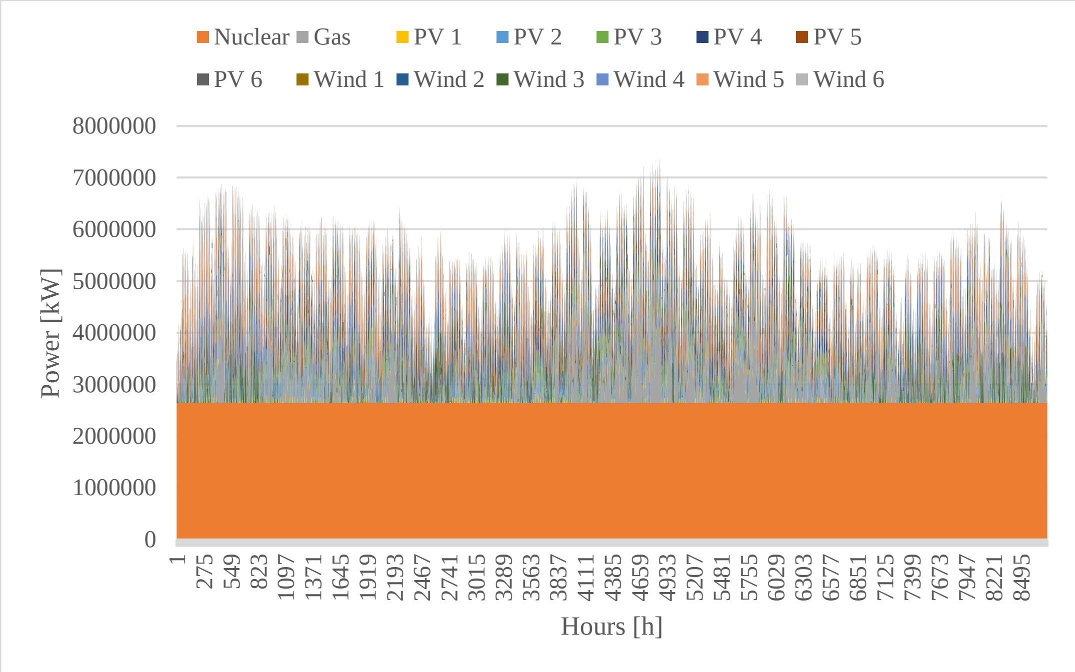


Illustration 35. Generation behaviour during a year.

In the previous results obtained for this simulation, the integration of wind power facilities plays a significant role in the energy mix. Wind power has a higher installed capacity compared to photovoltaics (solar), accounting for 29% of the total installed capacity. This indicates the importance of harnessing wind energy due to its relatively higher capacity factor (29.40% in average), which refers to the actual energy output of a renewable source compared to its maximum potential output.

The capacity factor of wind power is generally higher than that of photovoltaics, which means that wind turbines can generate electricity more consistently and for a larger portion of the time. This is because wind resources are available both during the day and night, while solar energy generation is dependent on the availability of sunlight. The intermittent nature of solar energy due to diurnal and seasonal variations makes the continuous availability of wind power a valuable asset in the energy mix.

By operating the nuclear energy facilities at full capacity throughout the projected model's lifetime of 50 years, the model ensures a constant baseline energy source. Combining this with the higher capacity factor of wind power, the energy system can achieve a more reliable and continuous supply of electricity while still incorporating renewable energy sources.

Overall, the model recognizes the significance of wind power in terms of its availability and capacity factor, making it a key contributor to the energy mix alongside nuclear and other conventional sources.

5.3.2 Case 2

In the new scenario with a progressive increase in the renewable energy share, the model incorporates the same technologies as in the previous case (wind power and photovoltaics) but with a changing mix of installed capacity. The purpose is to analyse the behaviour of the total installed capacity and its impact on the Levelized Cost of Energy (LCOE).

As the renewable energy share increases, the model assumes that more wind power and photovoltaic facilities are added to the energy mix. This progressive increase in renewable capacity allows for a greater utilization of clean and sustainable energy sources while reducing reliance on conventional sources such as nuclear and gas.

N°	Share	Total installed capacity [MW]	Capacity factor				Total LCOE [€/kWh]
			Nuclear	Gas	PV	Wind	
1	35%	13094	100%	12.41%	18.72%	30.54%	0.054
2	45%	14645	100%	13.35%	19.33%	31.82%	0.056
3	55%	16263	100%	14.06%	19.62%	32.04%	0.057
4	65%	17884	100%	14.67%	18.80%	32.88%	0.058
5	75%	19458	100%	15.59%	19.17%	33.50%	0.060
6	85%	23537	0%	12.47%	17.35%	26.69%	0.063

Table 8. Installed capacity, capacity factor, and LCOE for case 2 at different renewable share.

The information in Table 8 illustrates the capacity factors of different energy sources and how they are affected by the progressive increase in renewable energy share. It shows that as the renewable share increases, the capacity factors for gas and all renewable sources also increase until reaching 85% renewable share. At this point, there is a significant drop in the capacity factors of all renewable sources due to the sudden increase in installed capacity to replace the nuclear base.

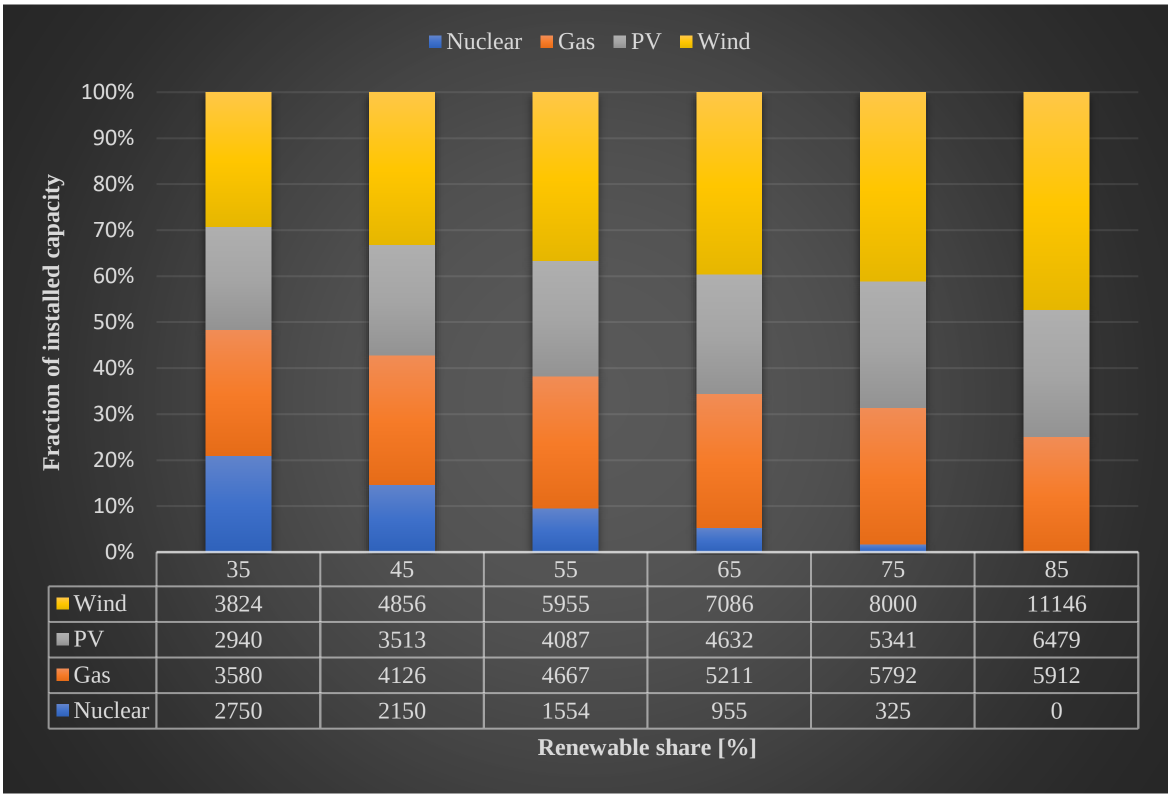


Illustration 36. Installed capacity [MW] vs renewable share for the case 2.

Illustration 36 provides a visual representation of the share of installed capacity specifically for wind energy. It shows that wind energy experiences a substantial increase in its share, starting from 29% at the initial 35% renewable share and reaching 47% at the 85% renewable share. This indicates the growing importance of wind power as the renewable share increases, highlighting its higher capacity factor compared to photovoltaics and its ability to provide a significant portion of the total installed capacity.

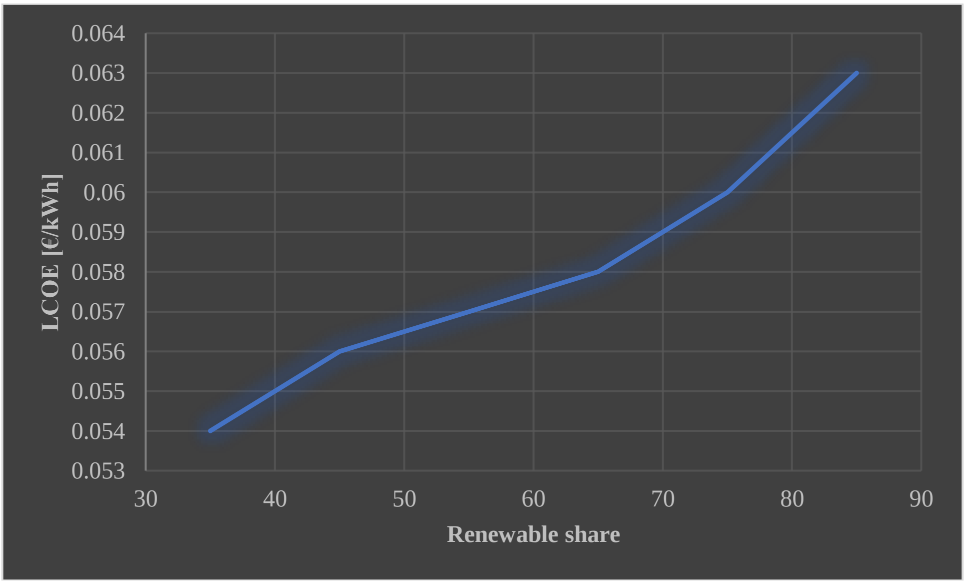


Illustration 37. LCOE evolution in function of renewable share for the case 2.

Illustration 37 demonstrates the relationship between the levelized cost of energy (LCOE) and the renewable share. It shows that as the renewable share increases, the LCOE of the system also increases. This indicates that the investment in renewable resources comes with a higher cost of implementation, particularly due to the unpredictable and variable nature of renewable sources like photovoltaics and wind power. To compensate for their intermittency, power plants need to be oversized, resulting in a lower capacity factor and higher overall costs compared to baseload generation sources such as nuclear and gas.

Overall, these findings suggest that the progressive increase in renewable share has implications for the capacity factors of different energy sources, with wind power playing a significant role. Additionally, the increase in renewable resources leads to higher LCOE, highlighting the challenges and costs associated with transitioning to a more renewable-based energy system. These insights can inform decision-making processes and help in evaluating the trade-offs between renewable integration and cost considerations.

5.3.3 Case 3

In Case 3, the focus is on the use of nuclear power plants as the sole non-renewable resource, while exploring the changes in renewable energy share. Unlike Case 2, nuclear energy is still present in the energy mix to maintain the renewable share, implying that the reduction in nuclear power leads to a significant increase in installed capacity for wind power.

N°	Share	Total installed capacity [MW]	Capacity factor				Total LCOE [€/kWh]
			Nuclear	Gas	PV	Wind	
1	35%	83248	100%	0%	12.45%	3.07%	0.218
2	45%	97667	100%	0%	10.37%	3.03%	0.223
3	55%	113869	100%	0%	11.02%	2.94%	0.254
4	65%	130106	100%	0%	11.14%	2.98%	0.285
5	75%	146802	100%	0%	10.19%	2.94%	0.318
6	85%	163886	100%	0%	7.29%	2.67%	0.353

Table 9. Installed capacity, capacity factor, and LCOE for case 3 at different renewable share.

One notable difference in Case 3 is the very low-capacity factor for wind power due to the need to compensate for the reduction in baseload generation. With the reduction in nuclear power, a higher installed capacity for wind power is required to ensure the renewable share. As a result, wind power facilities account for a substantial portion of the total installed capacity, ranging from 92% to 97% in this scenario.

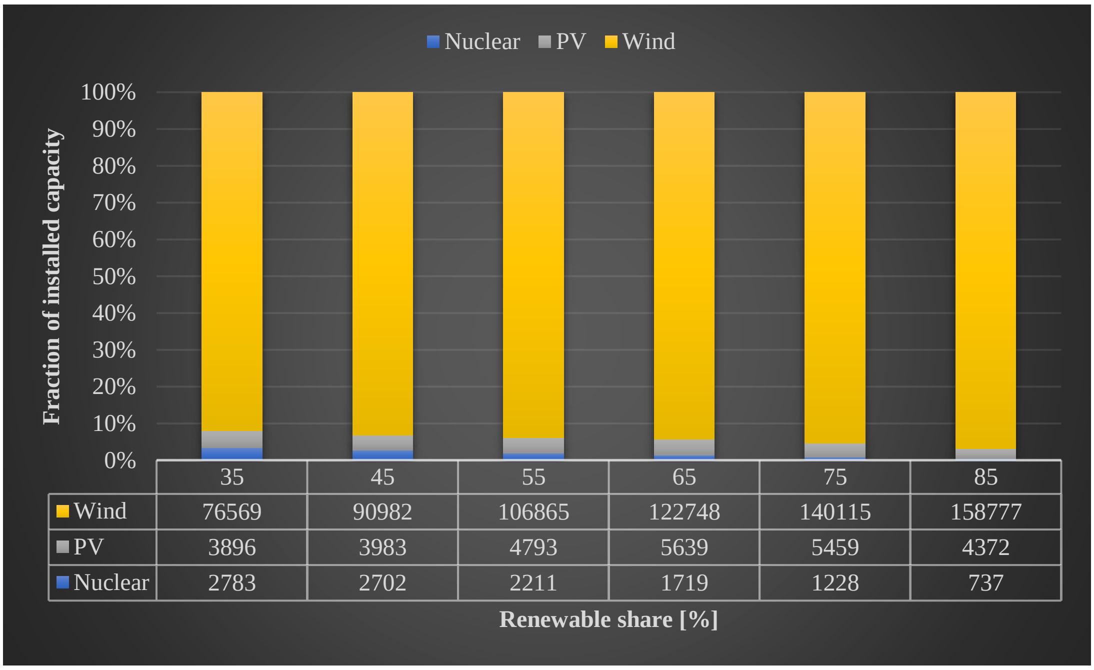


Illustration 38. Installed capacity [MW] vs renewable share for the case 3.

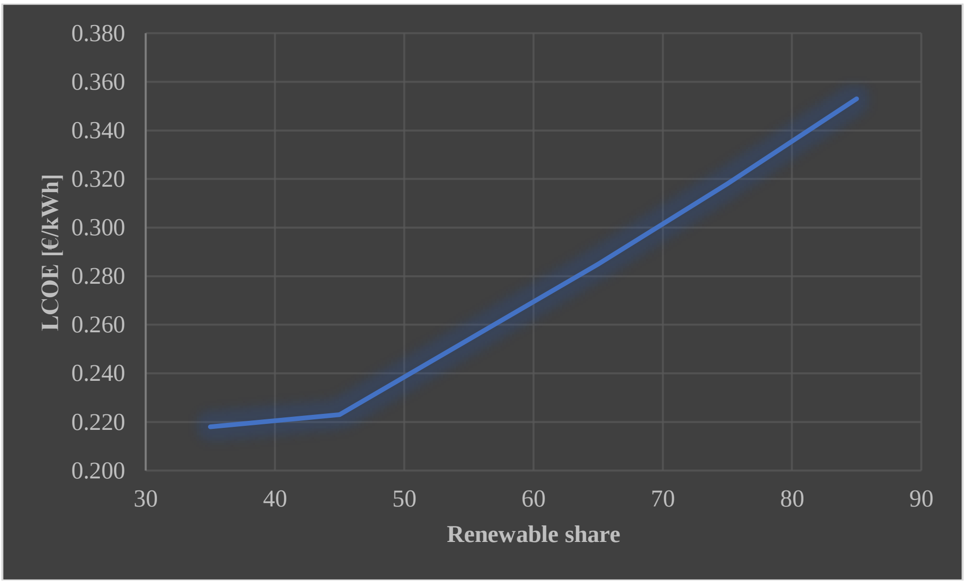


Illustration 39. LCOE evolution in function of renewable share for the case 3.

The high investment in wind power facilities, along with the need for significant capacity expansion, contributes to a higher levelized cost of energy (LCOE) compared to Case 2. The LCOE increases at a greater rate in Case 3 due to the substantial investment required for wind power to compensate for the reduction in nuclear generation. This indicates that the transition to a higher renewable share while maintaining nuclear power involves higher costs and involves challenges in terms of capacity planning and system integration.

The findings from Case 3 emphasize the trade-offs between renewable integration, the role of nuclear power, and the associated costs. It highlights the need for careful consideration of the energy mix and the balance between renewable and non-renewable sources to achieve a sustainable and cost-effective energy system.

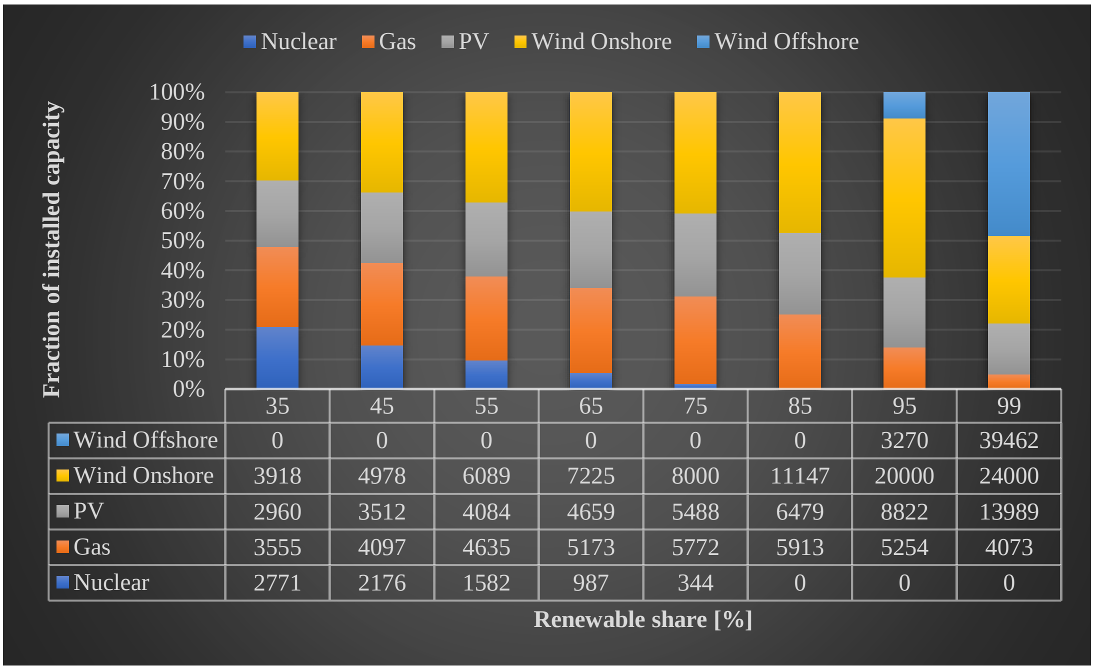
5.3.4 Case 4

In Case 4, offshore wind power is introduced as an additional energy source to the existing technologies in Case 2. The inclusion of offshore wind power adds another variable to consider, particularly due to its relatively high potential and associated costs.

N°	Share	Total installed capacity [MW]	Capacity factor					Total LCOE [€/kWh]
			Nuclear	Gas	PV	Wind Onshore	Wind Offshore	
1	35%	13204	100%	11.88%	12.42%	33.89%	0%	0.038
2	45%	14763	100%	12.85%	12.98%	34.89%	0%	0.043
3	55%	16389	100%	13.58%	13.56%	35.02%	0%	0.047
4	65%	18044	100%	14.17%	16.17%	33.72%	0%	0.051
5	75%	19604	100%	15.32%	14.08%	35.01%	0%	0.055
6	85%	23539	0%	12.47%	14.34%	27.89%	0%	0.069
7	95%	37347	0%	4.68%	11.71%	13.36%	29.51%	0.108
8	99%	81525	0%	1.21%	8.79%	14.05%	0.71%	0.130

Table 10. Installed capacity, capacity factor, and LCOE for case 4 at different renewable share.

Table 10 highlights an important observation: the optimization model only incorporates offshore wind power when the renewable share is close to 100%. This means that offshore wind power is considered necessary only when the other renewable technologies, such as onshore wind and photovoltaic, are unable to fully compensate for the reduction in gas facilities in the absence of nuclear power.



	35	45	55	65	75	85	95	99
Wind Offshore	0	0	0	0	0	0	3270	39462
Wind Onshore	3918	4978	6089	7225	8000	11147	20000	24000
PV	2960	3512	4084	4659	5488	6479	8822	13989
Gas	3555	4097	4635	5173	5772	5913	5254	4073
Nuclear	2771	2176	1582	987	344	0	0	0

Illustration 40. Installed capacity [MW] vs renewable share for the case 4.

Illustration 40 demonstrates the dominant role of wind power in the installed capacity share. As the renewable share increases, wind facilities (both onshore and offshore) benefit the most, while the contribution from photovoltaic remains relatively stable. This suggests that wind power, particularly offshore, becomes increasingly important in meeting the renewable energy targets.

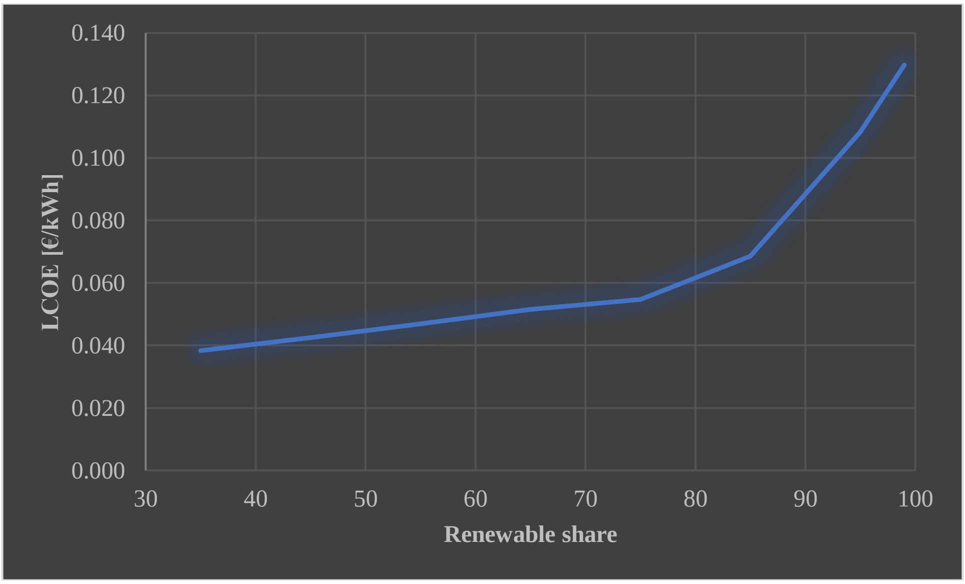


Illustration 41. LCOE evolution in function of renewable share for the case 4.

Illustration 41 shows a gradual increase in the levelized cost of energy (LCOE) until the renewable share reaches 85%. At this point, when offshore wind power is incorporated into the model, the LCOE increases significantly. This indicates that the addition of offshore wind power, with its associated higher costs, has a considerable impact on the overall cost of the energy system.

The findings from Case 4 highlight the trade-offs between renewable integration, the role of offshore wind power, and the associated costs. The model incorporates offshore wind power only when necessary, indicating the need to optimize the energy mix based on the capabilities and cost-effectiveness of different technologies. It emphasizes the importance of carefully evaluating the potential and cost implications of incorporating offshore wind power into the energy system.

5.3.5 Case 5

Case 5 builds upon Case 3, which explores the scenario without gas facilities, by incorporating hydrogen and hydropower facilities as renewable sources to provide a stable basis. The behaviour of hydrogen and hydropower facilities is modelled similar to a battery, as discussed in section 5.2.1.

Share	Total installed capacity [MW]	Capacity factor						
		Nuclear	Gas	PV	Wind Onshore	Wind Offshore	Hydrogen	Hydro
35%	93037	100%	0%	13.64%	28.99%	0%	1.25%	70.84%
45%	98302	100%	0%	19.73%	29.47%	0%	1.23%	68.84%
55%	105599	100%	0%	19.23%	28.01%	0%	1.30%	61.33%
65%	115151	100%	0%	12.58%	19.04%	13.08%	1.38%	77.81%
75%	128661	100%	0%	13.59%	21.61%	9.96%	1.12%	40.73%
85%	158147	100%	0%	13.91%	18.57%	50.15%	0.74%	60.05%
95%	199058	100%	0%	15.62%	20.72%	50.14%	0.59%	68.34%
99%	207755	100%	0%	13.80%	23.38%	9.20%	0.50%	77.62%

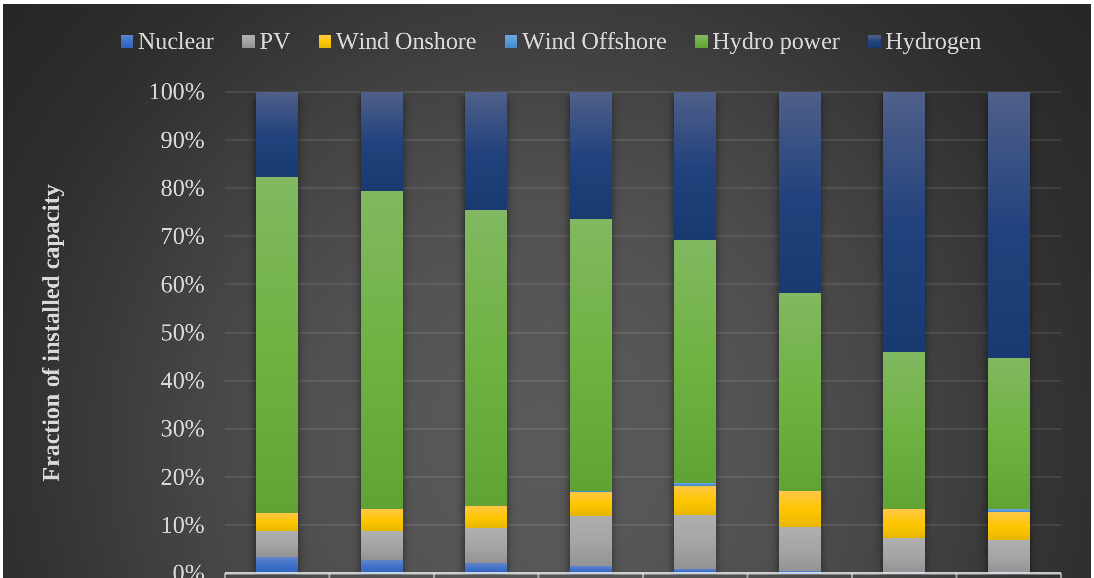
Table 11. Installed capacity and capacity factor for case 5 at different renewable share.

N°	Share	Total LCOE [€/kWh]
1	35%	0.044
2	45%	0.049
3	55%	0.055
4	65%	0.066
5	75%	0.084
6	85%	0.111
7	95%	0.149
8	99%	0.164

Table 12. LCOE for case 5 at different renewable share.

In contrast to Case 3, where onshore wind power exhibited a highly variable capacity factor ranging from 92% to 97% of the total installed capacity, Case 5 shows a more stable behaviour for onshore wind power in terms of capacity factor. This is likely due to the presence of hydrogen and hydropower facilities, which provide a renewable stable basis and help balance the variability of wind power.

Table 11 presents the capacity factor values for each technology, considering only electricity production. However, for hydrogen facilities, the capacity factor is much lower compared to other technologies because it only considers electricity production and not the full range of hydrogen production and utilization.



	35	45	55	65	75	85	95	99
Hydrogen	16400	20200	25800	30400	39400	66000	107400	114800
Hydro power	65000	65000	65000	65000	65000	65000	65000	65000
Wind Offshore	0	0	0	146	782	10	12	1506
Wind Onshore	3395	4489	4905	5753	7850	12000	12000	12000
PV	5048	5911	7683	12133	14400	14400	14400	14400
Nuclear	3194	2702	2211	1720	1228	737	246	49

Renewable share [%]

Illustration 42. Installed capacity [MW] vs renewable share for the case 5.

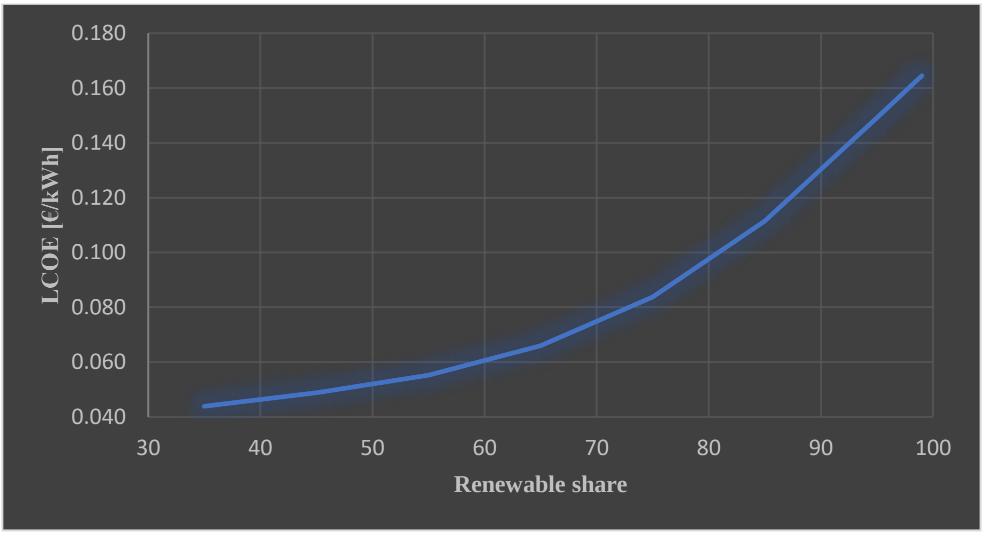


Illustration 43. LCOE evolution in function of renewable share for the case 5.

The increase in the levelized cost of energy (LCOE) in Case 5 exhibits a gradual and exponential behaviour. At lower renewable shares, the increase in LCOE is relatively smaller compared to higher shares. This suggests that the addition of renewable storage systems, such as hydrogen and hydropower, not only contributes to electricity production but also enables energy storage and management. Incorporating storage systems can help mitigate the impact of intermittent renewable sources and contribute to a more stable and balanced energy system.

The findings from Case 5 highlight the potential benefits of incorporating storage technologies, such as hydrogen and hydropower, to enhance the stability and reliability of the renewable energy system. By enabling energy storage and management, these technologies can help address the variability of renewable sources and contribute to a smoother integration of renewable energy into the grid.

5.3.6 Case 6

Case 6 builds upon Case 5 by doubling the hydropower capacity, with the aim of examining the behaviour of hydrogen facilities and offshore wind power.

Share	Total installed capacity [MW]	Capacity factor						
		Nuclear	Gas	PV	Wind Onshore	Wind Offshore	Hydrogen	Hydro
35%	148422	100%	0%	21.62%	30.57%	0%	2.49%	52.27%
45%	152961	100%	0%	22.76%	35.99%	0%	2.36%	55.99%
55%	157560	100%	0%	22.53%	36.45%	0%	1.99%	51.74%
65%	162270	100%	0%	22.78%	35.97%	0%	1.75%	60.08%
75%	168755	100%	0%	22.80%	36.17%	0%	1.82%	56.42%
85%	178544	100%	0%	19.00%	37.66%	18.03%	1.88%	59.12%
95%	191912	100%	0%	17.69%	33.42%	16.33%	1.64%	66.43%
99%	199846	100%	0%	15.96%	27.27%	13.42%	1.41%	65.12%

Table 13. Installed capacity and capacity factor for case 6 at different renewable share.

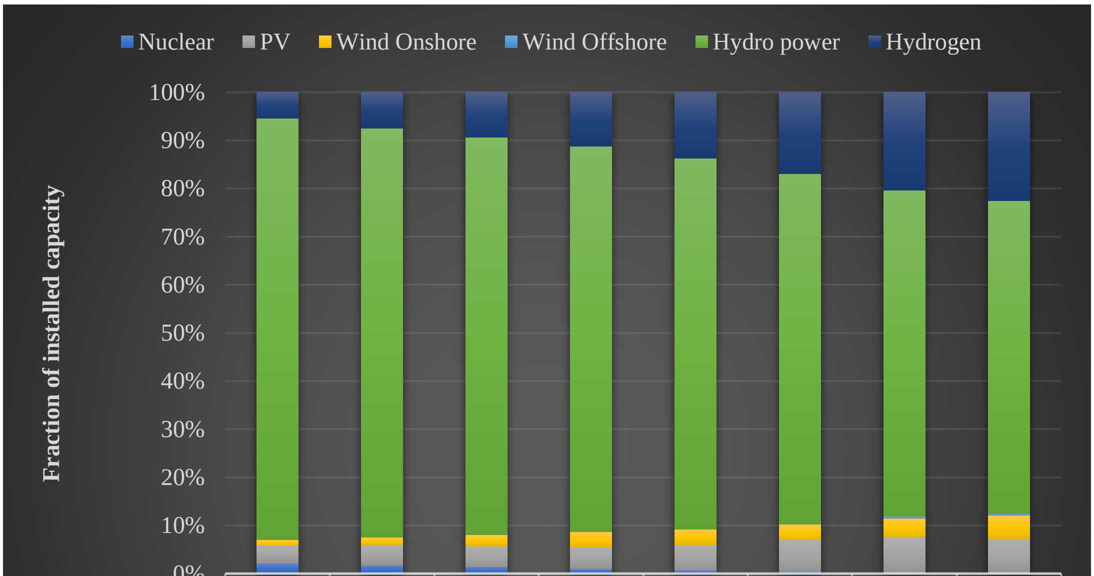
N°	Share	Total LCOE [€/kWh]
1	35%	0.033
2	45%	0.037
3	55%	0.041
4	65%	0.046
5	75%	0.051
6	85%	0.061
7	95%	0.078
8	99%	0.087

Table 14. LCOE for case 6 at different renewable share.

The increased hydropower capacity in Case 6 has a relatively smaller impact on the levelized cost of energy (LCOE) at higher renewable shares. This is likely due to the fact that hydropower facilities, acting as storage systems, help to balance the variability of renewable sources and contribute to a more stable energy system.

The addition of more hydropower facilities enables a smoother integration of renewable energy, reducing the need for oversized installations of solar and wind power to compensate for the absence of nuclear and gas facilities.

Table 13 shows that wind power facilities also exhibit greater stability in terms of capacity factor in Case 6. This further reinforces the role of storage systems, such as hydrogen and hydropower, in mitigating the intermittency of renewable sources and ensuring a more reliable and balanced energy supply.



	35	45	55	65	75	85	95	99
Hydrogen	8000	11400	14800	18200	23200	30200	39000	45000
Hydro power	130000	130000	130000	130000	130000	130000	130000	130000
Wind Offshore	0	0	0	0	0	110	795	575
Wind Onshore	1736	2401	3725	5200	5493	5692	7471	9822
PV	5492	6458	6824	7150	8834	11805	14400	14400
Nuclear	3194	2702	2211	1720	1228	737	246	49

Renewable share [%]

Illustration 44. Installed capacity [MW] vs renewable share for the case 6.

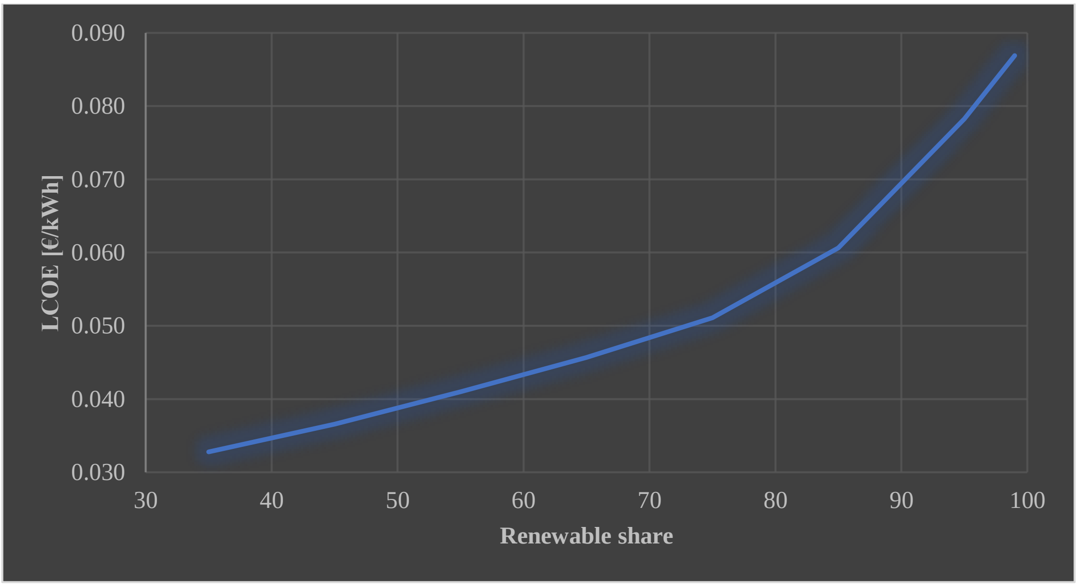


Illustration 45. LCOE evolution in function of renewable share for the case 6.

Furthermore, the incorporation of storage systems like hydrogen tanks and hydropower dams contributes to a reduction in the overall LCOE at higher penetration of renewable sources in the energy market. As the costs associated with storage systems decrease, the financial impact of integrating more renewable energy sources becomes more favourable, resulting in a lower LCOE.

The findings from Case 6 highlight the important role that storage systems play in facilitating the integration of renewable energy sources. By providing storage and balancing capabilities, hydrogen and hydropower systems help to enhance the stability, reliability, and cost-effectiveness of the renewable energy system, enabling a smoother transition to a more sustainable and renewable-oriented energy market.

6 Conclusions and future improvements

The analysis of the previous cases provides valuable insights into the integration of renewable energy sources and the role of storage systems in the energy system. Taking in consideration that the model operates into basic balance of energy, market dynamics are not considered, and some technical procedures used by the market operators were neglected. It is possible to have a general view of the behaviour of Catalonia's grid response in base to its demand and local resources.

The integration of renewable energy sources is crucial for transitioning to a sustainable and low-carbon energy system. However, understanding the behaviour and impacts of renewable sources, such as wind and solar power, as well as the role of storage systems, is essential for optimizing their integration and ensuring a reliable energy supply, this is more relevant as much as more renewable sources are introduced in the electric grid.

In this study, six different cases were examined to assess the behaviour of the energy system under varying renewable share scenarios, with special focus in the cases where the share of renewable is close to 100%. The cases considered the presence of nuclear energy, the inclusion of offshore wind power, and the incorporation of storage systems like hydrogen and hydropower.

The findings highlight several important conclusions. Firstly, as the renewable share increases, the capacity factors of renewable sources decrease, necessitating a larger installed capacity to maintain a reliable energy supply. The presence of nuclear energy provides a stable base generation, and its absence requires a significant increase in renewable capacity.

Offshore wind power emerges as a critical component when the renewable share is high, compensating for the reduced capacity factors of onshore wind power and enhancing system stability. Storage systems, such as hydrogen and hydropower, play a vital role in addressing the intermittency of renewable sources and stabilizing the energy system.

The study also emphasizes the impact of storage systems on the levelized cost of energy (LCOE). As renewable penetration increases, the LCOE tends to rise due to the need for additional capacity and storage costs. However, advancements in storage technology and cost reduction can help mitigate this increase over time.

Overall, these findings underscore the importance of a balanced energy mix, efficient storage technologies, and strategic planning to achieve a sustainable and cost-effective energy system. By optimizing the integration of renewable sources and storage systems, it is possible to ensure a reliable, affordable, and environmentally friendly energy supply for the future.

Incorporating hydrogen as an energy vector presents both opportunities and challenges in several scenarios. One of the significant challenges is the cost associated with installing storage systems, which require high-quality materials and safety measures. However, hydrogen offers several advantages, particularly its versatility. It can serve as a means of stabilizing energy systems, complementing technologies like reversible pumped hydropower facilities. Additionally, hydrogen can be utilized in various applications, including powering electric vehicles, serving as a backup energy storage solution, and providing heat for residential and commercial buildings.

The widespread adoption of hydrogen faces obstacles related to production, storage, distribution infrastructure, and costs. However, environmental policies that promote renewable energy sources and incentivize hydrogen usage can facilitate its broader adoption. Ongoing research and technological advancements are also focused on addressing these challenges and improving the efficiency and cost-effectiveness of hydrogen production, storage, and utilization. By overcoming these hurdles, hydrogen has the potential to play a significant role in achieving a cleaner and more sustainable energy future.

Further studies can be conducted to explore various aspects related to the dynamic behaviour of the grid and its response to demand, as well as other considerations such as grid restrictions, physical constraints, and political agreements.

Investigating the impact of grid losses on the cost of energy in different regions. This could involve studying the efficiency of energy transmission and distribution systems, identifying areas with high losses, and exploring strategies to mitigate these losses.

Examining the potential for hydrogen to be traded not only as a fuel but also as a provider of ancillary services to the grid. This could involve studying the technical and economic feasibility of using hydrogen to support grid stability, frequency regulation, and voltage control.

Assessing the impact of incorporating hydrogen systems into renewable plants such as PV or wind power. This could involve analysing the effect on the Levelized Cost of Energy (LCOE) and the ability to stabilize renewable energy production by utilizing hydrogen storage to compensate for intermittent generation and enable the provision of electricity on-demand for longer durations.

Conducting comprehensive techno-economic analyses to evaluate the cost-effectiveness of hydrogen systems in various energy scenarios. This could include assessing the cost of hydrogen production, storage, and distribution, as well as analysing the potential revenue streams and market opportunities associated with hydrogen as a versatile energy carrier.

Investigating the policy and regulatory frameworks necessary to support the integration and deployment of hydrogen technologies. This could involve studying the development of hydrogen-specific regulations, financial incentives, and market mechanisms to encourage investment, innovation, and the adoption of hydrogen solutions.

By conducting these studies, policymakers, researchers, and industry stakeholders can gain valuable insights into the potential benefits and challenges of incorporating hydrogen into the energy landscape. This knowledge can inform future decisions, strategies, and investments to facilitate the transition to a more sustainable and resilient energy system.

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8 Nomenclature

$[(x_{HP})_{Char}]_{[t][i]}$	Instant reversible hydropower facility consumption for a specific time t for each plant i.	$[kW]$
$[(x_{HP})_{Char}]_{[t+1][i]}$	Next instant reversible hydropower facility consumption $t+1$ for each plant i.	$[kW]$
$[(x_{HP})_{Dis}]_{[t][i]}$	Instant reversible hydropower facility production for a specific time t for each plant i.	$[kW]$
$[(x_{HP})_{Dis}]_{[t+1][i]}$	Next instant reversible hydropower facility production $t+1$ for each plant i.	$[kW]$
$\left[(x_{Hy})_{Ab}\right]_{[t][i]}$	Instant electrolyser power consumption (power absorbed from grid) for a specific time t for each facility i.	$[kW]$
$\left[(x_{Hy})_{Ab}\right]_{[t+1][i]}$	Next instant electrolyser power consumption for a specific time $t+1$ for each plant i.	$[kW]$
$\left[(x_{Hy})_{Gen}\right]_{[t][i]}$	Instant fuel cell power generation for a specific time t for each facility i.	$[kW]$
$\left[(x_{Hy})_{Gen}\right]_{[t+1][i]}$	Next instant hydrogen fuel cells power production for a specific time $t+1$ for each plant i.	$[kW]$
$(E_{Res})_{Min}$	Minimum allowed energy stored for all dams in hydropower facilities.	$[kWh]$
$(E_{Res})_{max}$	Maximum allowed energy stored for all dams in hydropower facilities.	$[kWh]$
$(E_{Tank})_{Min}$	Minimum allowed energy stored for all hydrogen facility tanks.	$[kWh]$
$(E_{Tank})_{max}$	Maximum allowed energy stored for all hydrogen facility tanks.	$[kWh]$
$(x_{HP})_{[t][i]}$	Instant Hydropower for a specific time t for each plant i.	$[kW]$
$(x_{HP})_{[t+1][i]}$	Next instant Hydropower production $t+1$ for each plant i.	$[kW]$
$(x_{Nu})_{[t][i]}$	Instant nuclear power for a specific time t for each plant i.	$[kW]$
$(x_{PV})_{[t][i]}$	Instant photovoltaic power for a specific time t for each plant i.	$[kW]$
$(x_{WP})_{[t][i]}$	Instant wind power for a specific time t for each plant i.	$[kW]$
$(x_{WP})_{[t+1][i]}$	Next instant wind power production $t+1$ for each plant i.	$[kW]$
A_b	Swiped projected of blades.	$[m^2]$
A_c	Collector surface.	$[m^2]$
A_{cell}	Solar cell surface.	$[m^2]$
C_p	Specific heat.	$\left[\frac{J}{kg \cdot K}\right]$
$D_{[t]}$	Power demanded in a specific time t.	$[kW]$
D_n	Diffusion coefficient of electrons.	$\left[\frac{m^2}{s}\right]$

D_p	Diffusion coefficient of holes.	$\left[\frac{1}{m^3}\right]$
$E_{Ab[t][i]}$	Energy absorbed from grid to produce hydrogen at a time t for each plant i.	$[kWh]$
$E_{Char[t][i]}$	Energy transferred from the grid to the reservoir in actual time t for each plant i.	$[kWh]$
$E_{Dis[t][i]}$	Energy transferred from the reservoir to the grid in actual time t for each plant i.	$[kWh]$
$E_{Gen[t][i]}$	Energy produced to the grid at a time t for each plant i.	$[kWh]$
$E_{Res[t-1][i]}$	Energy stored in a previous stage $t-1$ for each plant i.	$[kWh]$
E_{Res}	Global energy stored in all reservoirs.	$[kWh]$
$E_{Tank[t-1][i]}$	Energy stored in a previous stage $t-1$ for each plant i.	$[kWh]$
E_{Tank}	Global energy stored in all hydrogen facility tanks.	$[kWh]$
E_t	Total energy produced each year.	$[kWh]$
F_R	Removal factor.	
$G_{e[t]}$	Power generated for all producers in a specific time t.	$[kW]$
I_α	Solar energy absorbed.	$\left[\frac{W}{m^2}\right]$
J_{max}	Maximum current density at maximum power point in.	$\left[\frac{A}{m^2}\right]$
J_o	Dark current density.	$\left[\frac{A}{m^2}\right]$
J_{ph}	Photocurrent density.	$\left[\frac{A}{m^2}\right]$
J_{sc}	Short circuit current density.	$\left[\frac{A}{m^2}\right]$
$P_{El[t][i]}$	Electrolyser power installed for a specific time t for each plant i.	$[kW]$
$P_{HFC[t][i]}$	Hydrogen fuel cell power installed for a specific time t for each plant i.	$[kW]$
$P_{HP[t][i]}$	Hydropower installed for a specific time t for each plant i.	$[kW]$
$P_{Nu[t][i]}$	Nuclear power installed for a specific time t for each plant i.	$[kW]$
$P_{P[t][i]}$	Hydropower pumps installed for a specific time t for each plant i.	$[kW]$
$P_{PV[t][i]}$	Photovoltaic power installed for a specific time t for each plant i.	$[kW]$
$P_{T[t][i]}$	Hydropower turbines installed for a specific time t for each plant i.	$[kW]$
$P_{WP[t][i]}$	Wind power installed for a specific time t for each plant i.	$[kW]$
P_{light}	Solar power per surface unit.	$\left[\frac{W}{m^2}\right]$
Q_u	Useful thermal power.	$[W]$

R_P	Shunt resistance.	$[\Omega]$
R_s	Series resistance.	$[\Omega]$
S_b	Passivated back surface.	$\left[\frac{m}{s}\right]$
S_f	Passivated frontal surface.	$\left[\frac{m}{s}\right]$
T_a	Ambient temperature.	$[°C\ or\ K]$
T_{fi}	Inlet fluid temperature.	$[°C\ or\ K]$
T_{fo}	Outlet fluid temperature.	$[°C\ or\ K]$
U_L	Overall heat coefficient of a flat plate collector.	$\left[\frac{W}{m^2 \cdot K}\right]$
V_T	Cell voltage by temperature effect.	$[V]$
V_{max}	Maximum voltage at maximum power point.	$[V]$
V_{oc}	Open circuit voltage.	$[V]$
W_n	Width of "n" junction.	$[m]$
W_p	Width of "p" junction.	$[m]$
$\dot{m}$	Mass flow.	$\left[\frac{kg}{s}\right]$
n_o	Carrier density for electrons.	$\left[\frac{1}{m^3}\right]$
p_o	Carrier density for holes.	$\left[\frac{1}{m^3}\right]$
$CAPEX_{El}$	Capital expenses for electrolysers in hydrogen production plants.	$\left[\frac{€}{kW}\right]$
$CAPEX_{HFC}$	Capital expenses for hydrogen fuel cells in hydrogen production plants.	$\left[\frac{€}{kW}\right]$
$CAPEX_{HP}$	Capital expenses for hydropower plants.	$\left[\frac{€}{kW}\right]$
$CAPEX_{Non-Ren}$	Capital expenses for non-renewable resources.	$[€]$
$CAPEX_{Nu}$	Capital expenses for nuclear plants.	$\left[\frac{€}{kW}\right]$
$CAPEX_P$	Capital expenses for pumps in reversible hydropower plants.	$\left[\frac{€}{kW}\right]$
$CAPEX_{PV}$	Capital expenses for photovoltaic plants.	$\left[\frac{€}{kW}\right]$
$CAPEX_{Ren}$	Capital expenses for renewable resources.	$[€]$
$CAPEX_T$	Capital expenses for turbines in reversible hydropower plants.	$\left[\frac{€}{kW}\right]$
$CAPEX_{WP}$	Capital expenses for wind power plants.	$\left[\frac{€}{kW}\right]$
$CAPEX$	Capital Expenditures.	$[€]$
FC	Fuel Cost.	$[€]$
FF	Fill factor.	$[\%]$
G	Generation rate.	$\left[\frac{1}{m^3 \cdot s}\right]$
I	Incidence radiation.	$\left[\frac{W}{m^2}\right]$
J	Current density.	$[m^2]$
$LCOE_{Non-Ren}$	Levelized cost of energy for non-renewable resources.	$\left[\frac{€}{kWh}\right]$

$LCOE_{Ren}$	Levelized cost of energy for renewable resources.	$\left[\frac{€}{kWh}\right]$
$LCOE$	Levelized Cost of Energy.	$\left[\frac{€}{kWh}\right]$
$OPEX_{El}$	Operative and maintenance expenses for electrolyser in hydrogen production plants.	$\left[\frac{€}{kW}\right]$
$OPEX_{HFC}$	Operative and maintenance expenses for hydrogen fuel cells in hydrogen production plants.	$\left[\frac{€}{kW}\right]$
$OPEX_{HP}$	Operative and maintenance expenses for hydropower plants.	$\left[\frac{€}{kW}\right]$
$OPEX_{Non-Ren}$	Operative and maintenance expenses for non-renewable resources.	[€]
$OPEX_{Nu}$	Operative and maintenance expenses for nuclear plants.	$\left[\frac{€}{kW}\right]$
$OPEX_{P}$	Operative and maintenance expenses for pumps in reversible hydropower plants.	$\left[\frac{€}{kW}\right]$
$OPEX_{PV}$	Operative and maintenance expenses for photovoltaic plants.	$\left[\frac{€}{kW}\right]$
$OPEX_{Ren}$	Operative and maintenance expenses for renewable resources.	[€]
$OPEX_{T}$	Operative and maintenance expenses for turbines in reversible hydropower plants.	$\left[\frac{€}{kW}\right]$
$OPEX_{WP}$	Operative and maintenance expenses for wind power plants.	$\left[\frac{€}{kW}\right]$
$OPEX$	Operative and Maintenance Expenditures.	[€]
P	Available wind power.	$[W]$
RC	Replacement expenditures.	[€]
T	Temperature.	$[°C\ or\ K]$
V	Voltage between terminals.	$[V]$
$f(x)$	Objective function.	$\left[\frac{€}{kWh}\right]$
i	Discount rate.	[%]
k	Stefan-Boltzmann constant (1.38×10^{-23}).	$\frac{J}{K}$
n	Ideality factor.	
q	Elemental charge (1.60×10^{-19}).	$[C]$
t	Time.	$[s, min, h\ or\ years]$
v	Velocity.	$\left[\frac{m}{s}\right]$
α	Absorptivity.	
ε	Emissivity.	
η	Efficiency.	[%]
ρ	Density.	$\left[\frac{kg}{m^3}\right]$
ρ	Reflectivity.	
τ	Transmissivity.	