POLYTECHNIC OF TURIN

Master's Degree in Energy and Nuclear Engineering
Renewable energy systems

Master's Degree Thesis

Modelling the long-term evolution of the Italian energy system: The role of renewable resources and energy storage facilities

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Abstract

Climate change is a worldwide issue which is causing several difficulties and consequences both at human and environmental level. The energy sector is one of the main contributors to greenhouse gas (GHG) emissions and thus policy challenges are the main tool to contain this crisis. Indeed, a necessary path to intervene is the transition from traditional fossil fuels use toward the renewable sources, therefore leaving the carbon-based electricity generation in favour of an energy mix based on a higher renewable share and the residual part on gas.

The aim of this thesis is to elaborate an energy model of the Italian energy system by performing long-term planning of energy evolution. In particular, it is investigated the key role of photovoltaic and onshore and offshore wind resources, by coupling them with power-to-power (P2P) systems based on hydrogen and batteries. The OSeMOSYS (Open-Source energy Modelling System) tool is used to develop those energy strategies at Italian national level. OSeMOSYS is a deterministic, linear optimization long-term modelling framework, based on the minimization of the net present cost of the energy system. An enhanced version is used, applying a specific approach for the time series representation, which is the clustering method. In this way, representative days (RDs) of the different years are defined considering specific attributes, such as the demand and the supply sides. A sensitivity analysis is performed to identify the optimal number of representative days as a compromise between the computational time and the solution accuracy, by means of a simplified base scenario.

The starting point of the energy model is the potential assessment of both photovoltaic and wind onshore resources in order to determine their actual technical availability. It is used the Geographical Information Systems (GIS), which is a useful tool to manipulate and analyse spatial and geographical data. Subsequently, three main scenarios are elaborated aiming to determine the feasibility of renewable penetration in the electricity grid, by means of P2P systems. In particular, Li-ion batteries and hydrogen storage are the new energy storage technologies introduced in order to avoid an oversizing of renewable systems and allow a higher flexibility of the electricity system itself. Three main scenarios are elaborated varying the storage technology: only-battery (OB), only-hydrogen (OH) and a hybrid battery-hydrogen scenario (BH).

Results from the techno-economic optimization show that the BH scenario is preferrable: a cost-effective energy system is achieved combining the renewable

energy systems with the storages facilities, leading to more than 60% of variable renewable energy sources (VRES) in the final energy mix production. Therefore, it is possible and feasible to achieve a high renewable share in the energy mix able to meet the future energy and climate challenges.

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Actual World Scenario

The Kyoto protocol was signed in 1997 by 192 Parties, in order to operationalize the United Nation Framework Convention on Climate Change of 1994. It was the first time in which a global climate problem was recognized and some specific goals were set. In particular, the Convention asked industrialized countries and developing counties to limit and reduce the greenhouse gases (GHG) emission by means of specific policies and measures of mitigation [1].

Moreover, in 2015 the Paris Agreement, which was adopted by 196 Parties at COP21, set a new target in order to deal with the climate change. The goal was to limit the global warming below 2°C, preferably to 1.5°C, with respect to pre-industrial level, and also the final aim was to reach a climate neutral world by mid-century. In particular, the electricity sector is the one which needs more efforts in order to arrive at a net zero energy system, due to its direct effects towards the environment depending on how and where the electricity is generated and delivered.

Considering the energy sector, the energy production and use account for two thirds of the world's greenhouse gases (GHG) emissions, therefore all the pledges of the COP21 have to determine cuts in these emissions, but also keeping sustaining the world growth, guaranteeing the energy security and bringing energy to countries which lack it. In fact, 940 million people, thus the 13% of the world population do not have any access to electricity (figure 1.1).

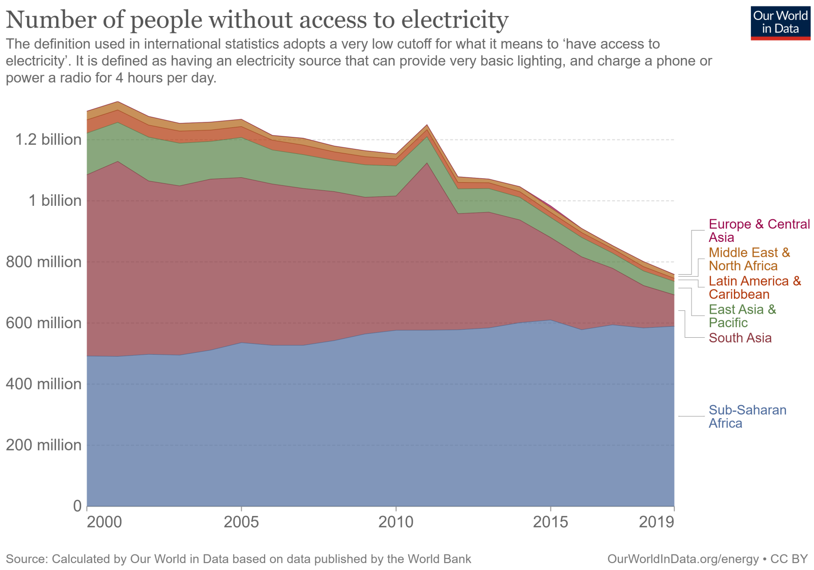


Figure 1.1: Number of people without access to electricity [2].

Concerning the fuel use, nowadays there is still a strong fossil fuels use. The issue is that they are the largest sources of CO_2 emissions (figure 1.2), which are together with other greenhouse gases, such as methane and nitrous oxide, the main cause of the actual critical climate change. Thus, the aim is to shift the energy system towards a low-carbon sources of energy [3]. Though it is a problem at world level, countries behave in a different way, depending on their economic state: emerging markets and developing economies account for the higher share of global emissions, while advanced economies are in a structural decline.

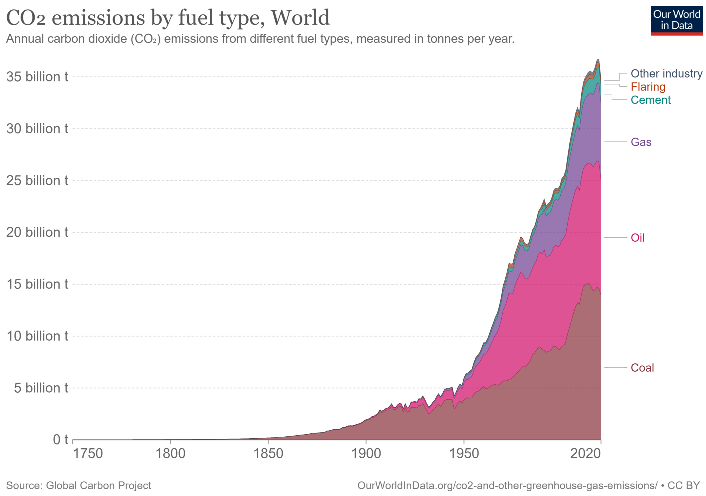


Figure 1.2: Annual CO_2 emissions from different fuel types, measured in tonnes per year [2].

Another important point is the global energy consumption. In fact, it is increasing in the years. Therefore, it is a complex situation: on one hand it is necessary to cover the higher energy demand also raising the living standard of many countries in the world, but on the other hand it is necessary to proceed limiting as much as possible the fossil fuels use.

As shown in figure 1.3, the global energy supply still rely on fossil fuel with a

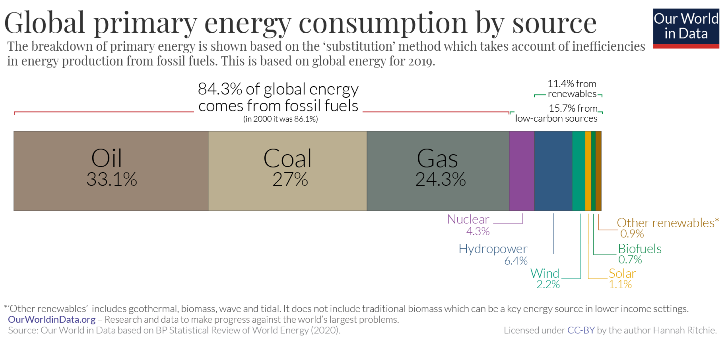


Figure 1.3: Global primary energy consumption by source [2].

low-carbon energy's share in the total energy mix, which is increasing very slowly. The key point in order to shift towards a low-carbon energy system rely on the renewable energy sources (RES), though from the beginning of the millennium in 2000 to 2021 the RES increase was only of the 3% points [2].

Nevertheless, it is important to state that renewable penetration creates difficulties both in term of grid stability and mismatch between demand and supply. Those problems are associated to the intermittent nature of most of the renewable resources, such as wind and solar. Moreover, RESs are abundant in nature, eco-friendly, modular and can be applied in different sectors, such as industrial, commercial, agricultural and residential. In order to overcome their main limitations, such as that they are non-dispachable and unable to follow the load demand, different approaches are done and a significant role is played by the Energy Storage Systems (ESS). In particular, they are able to solve the intermittency issue due to the fact that most of the RES depends on the atmospheric conditions. The main point is that EES can store energy during high electricity production or when the demand is small [3]. Other ways to deal with the RES issues are the demand management, the distributed generation, micro-grids and also smart grids [4].

1.2 European Scenario

The European Union is responsible only for the 8% of world CO_2 emission, but it is also responsible for one of the higher share of cumulative emissions. Therefore, it wants to act in order to move towards a greener economy. It aims to overcome both the climate change and the environmental decline by means of specific policies. In particular, by means of the Green Deal the European Union wants to be net zero emission by 2050, and to reduce the net GHG emission of the 55% by 2030 with respect to the level in 1990 [5].

Moreover, with the Fit for 55 package, the Europe gives a series of interconnected proposals, all driven by the same final goal, which is a competitive and green transition by 2030 (figure 1.4). This package consists in different initiatives regarding different aspects of the society: climate, energy and fuels, transport, buildings, land use and forestry [6].

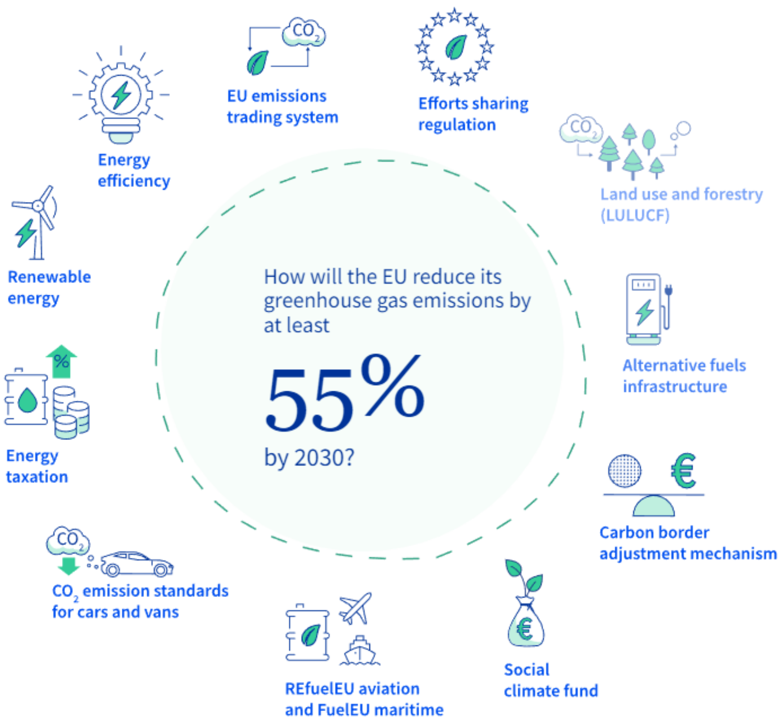


Figure 1.4: EU Fit for 55 proposals [6].

In particular, by means of this program, the different proposal are done in order to ensure that the different EU policies are in line with the climate goals agreed by the Council and the European Parliament. Europe will reduce its greenhouse gas emission by 55% by 2030 by means of different interventions:

- EU emissions trading system: it is proposed a set of changes to the existing EU's emission trading system (ETS) in order to have an overall emission reduction in sectors of 61% by 2030 compared with 2050.
- Member states' emissions reduction targets: it is proposed an increase of the EU-level greenhouse gas emission reduction target from 29% to 40%, compared with 2005, updating the actual national targets.
- Emissions and removals from land use, land use change and forestry: it is necessary to improve the carbon removals and the natural carbon sink in EU.
- Renewable energy: it is proposed to increase the current EU target of renewable energy sources in the energy mix to 40% by 2030.
- Energy efficiency: it is proposed to increase the current EU target of energy efficiency from 32.5% to 36% for final and 39% for primary energy consumption.
- Alternative fuel infrastructure: it is proposed an acceleration of the deployment of infrastructure for recharging or refuelling vehicles with alternative fuels and to provide an alternative power supply for ships in port and stationary aircraft.
- CO_2 emission standards for cars and vans: it is proposed to increase EU reduction targets for 2030 and to set a new target of 100% for 2035.
- Energy taxation: it is proposed a taxation for both the energy products and electricity.
- Carbon border adjustment mechanism (CBAM): the aim is to avoid that the emission reduction efforts are counterbalanced by increasing the emissions outside through the relocation of production in non-EU countries.
- Sustainable aviation fuels: the aim is to strongly reduce aircraft emissions.
- Greener fuels shipping: the aim of using renewable low-carbon fuel as in maritime transport is to reduce the greenhouse gas intensity of the energy used on-board by ships to 50% by 2050.
- Social climate fund (SCF): the aim is to address the social and distributional impact of the proposed emission targets for buildings and road transport. In particular, the fund aims to support households, micro-enterprises and

transport users using €72 billion over the 2025-2032 period. The SCF is an additional spending line for the EU budget, financed largely from the EU's own resources. In addition, by means of the Annex I, it is assessed the maximum financial allocation from the SCF for each EU member state. It depends on the total population, the population at risk term of poverty, on the gross national income (GNI) per capita, the overall GHG emissions and the CO_2 emissions from fuel combustion by households. Italy will receive one of the higher share of the SCF, the 10.8%.

1.3 Italian Scenario

Italy shares the European plan and aims to reinforce the effort for the decarbonization aligning itself to the Green New Deal, as a green pact promoting economic and social sustainability, also considering the compatibility with the ambient safeguard targets [7]. In the last decade, the commitments to sustain renewable energies and energy efficiency have grown and different objectives are pursued, such as:

- Accelerate the decarbonization process in the energy sector
- Promote the autoconsumption and energy communities
- Promote the energy system evolution, in particular in the electricity sector based on renewable sources
- Guarantee the energy supply, considering both energy security and continuity
- Promote the energy efficiency in all sectors
- Promote the electrification in the consumption, especially in the civil and transport sectors
- Promote the research and the innovation in the energetic system
- Promote precautions in order to reduced potential negative impacts of the energetic transformation, such as the air quality, the land consumption and the landscape safeguard

For what concerns the decarbonization process, the objective is to accelerate the transition from traditional fossil fuels toward the renewable sources, leaving the carbon use for the electricity generation in favour of a energetic mix based on a higher renewable share and the residual part on gas.

Concerning the Italian efforts in order to reduce the CO_2 emissions, thermoelectrical and industry sector, which are driven by EU ETS, will face a higher CO_2 price with respect to the last decades, in order to contribute to the carbon phase out by 2025, whereas the substitute plants and the necessary infrastructure will be ready. For the other sectors, which are driven by the Effort Sharing Regulation (ESR), other measures will be promoted considering both the potential and the costs of reduction emissions. The higher contributions will be the one of the transport and civil sector, combining both efficiency improvements and renewable exploitation. In figure 1.5, the main European and Italian energy and climate targets are shown.

	Obiettivi 2020 UE	Obiettivi 2020 ITALIA	Obiettivi 2030 UE	Obiettivi 2030 ITALIA (PNIEC)
Energie rinnovabili (FER)				
Quota di energia da FER nei Consumi Finali Lordi di energia	20%	17%	32%	30%
Quota di energia da FER nei Consumi Finali Lordi di energia nei trasporti	10%	10%	14%	22%
Quota di energia da FER nei Consumi Finali Lordi per riscaldamento e raffrescamento			+1,3% annuo (indicativo)	+1,3% annuo (indicativo)
Efficienza energetica				
Riduzione dei consumi di energia primaria rispetto allo scenario PRIMES 2007	-20%	-24%	-32,5% (indicativo)	-43% (indicativo)
Risparmi consumi finali tramite regimi obbligatori efficienza energetica	-1,5% annuo (senza trasp.)	-1,5% annuo (senza trasp.)	-0,8% annuo (con trasporti)	-0,8% annuo (con trasporti)
Emissioni gas serra				
Riduzione dei GHG vs 2005 per tutti gli impianti vincolati dalla normativa ETS	-21%		-43%	
Riduzione dei GHG vs 2005 per tutti i settori non ETS	-10%	-13%	-30%	-33%
Riduzione complessiva dei gas a effetto serra rispetto ai livelli del 1990	-20%		-40%	
Interconnettività elettrica				
Livello di interconnettività elettrica	10%	8%	15%	10%[1]
Capacità di interconnessione elettrica (MW)		9.285		14.375

Figure 1.5: Main European and Italian energy and climate targets by 2020 and 2030 [7].

1.3.1 Electrical sector

Considering the objectives of the national plan, the electricity generation fleet will face a huge transformation due to the phase out aim of the coal generation yet by 2025. The higher renewable increase will be due by the electrical sector, which will reach 16 Mtoe of generation by RES, equal to 187 TWh. In particular, there will be a high penetration of photovoltaic and wind energy, covering the 55% of the final electricity gross consumption. Thus, the electricity production by those renewable sources should respectively triple and double by 2030. The other renewable sources will face a contained increase, in particular for the geothermal and hydroelectric sources, while the bioenergies will face a slight increase. Figures 1.6, 1.7 and 1.8 show NEPC targets for the electric sector.

Fonte	2016	2017	2025	2030
Idrica	18.641	18.863	19.140	19.200
Geotermica	815	813	920	950
Eolica	9.410	9.766	15.950	19.300
di cui off shore	0	0	300	900
Bioenergie	4.124	4.135	3.570	3.760
Solare	19.269	19.682	28.550	52.000
di cui CSP	0	0	250	880
Totale	**52.258**	**53.259**	**68.130**	**95.210**

Figure 1.6: Power targets (MW) from renewable sources by 2030 [7].

	2016	2017	2025	2030
Produzione rinnovabile	**110,5**	**113,1**	**142,9**	**186,8**
Idrica (effettiva)	42,4	36,2		
Idrica (normalizzata)	46,2	46,0	49,0	49,3
Eolica (effettiva)	17,7	17,7		
Eolica (normalizzata)	16,5	17,2	31,0	41,5
Geotermica	6,3	6,2	6,9	7,1
Bioenergie*	19,4	19,3	16,0	15,7
Solare	22,1	24,4	40,1	73,1
Denominatore - Consumi Interni Lordi di energia elettrica	**325,0**	**331,8**	**334**	**339,5**
Quota FER-E (%)	**34,0%**	**34,1%**	**42,6%**	**55,0%**

Figure 1.7: Energy targets (TWh) from renewable sources by 2030 [7].

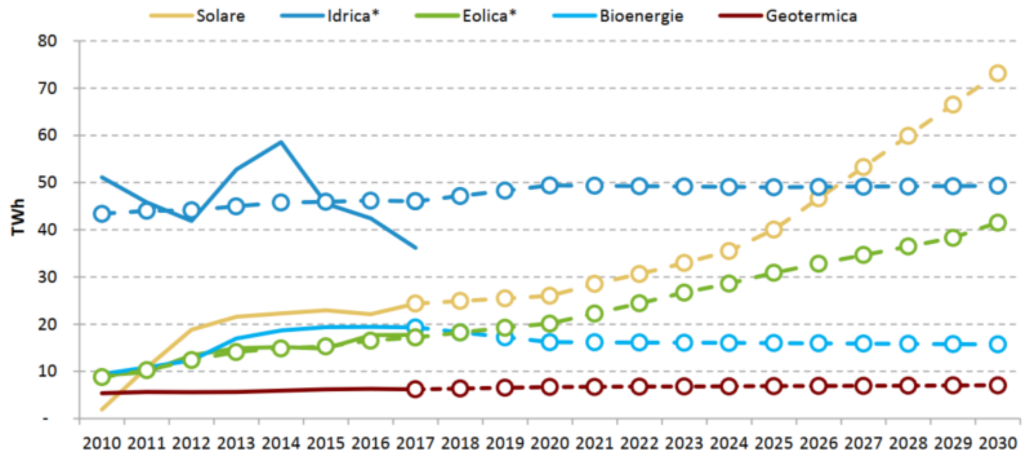


Figure 1.8: Trajectory of energy from renewable sources by 2030 [7].

1.4 Italian Electric system

The Italian electric market is composed by four parts: the electricity production, which is done by means of both fossil fuels and renewable sources, the electricity transmission, the electricity distribution and the final dispachment to the end users.

Moreover, the italian electric market was liberalized since 1999 and the transmission part is lead by TERNA. It is responsible for the transmission, thus the management, the development and the maintenance of the national electrical grid at high voltage, and for the dispachment, which consists in the continuous management of the electricity fluxes. TERNA operates in a natural monopoly regime and within a market which is regulated by the Regulation Authority for energy, networks and Ambient (ARERA).

In addition, TERNA is part of the ENTSO-E, which is the European Network of Transmission Sysyem Operator for Electricity. Thus, ENTSO-E is an association for the cooperation of the European transmission system operators (TSOs). It is composed by 39 TSOs members, representing 35 countries, which are responsible for the security and coordination of the European electricity system, which is the larges interconnected electrical grid in the world [8].
As it is possible to appreciate from the figure 1.9, Italy is divided in specific regions:

- ITCN: Italy Central North
- ITCS: Italy Central South
- ITN1: Italy North
- ITS1: Italy South
- ITSA: Italy Sardinia
- ITSI: Italy Sicily

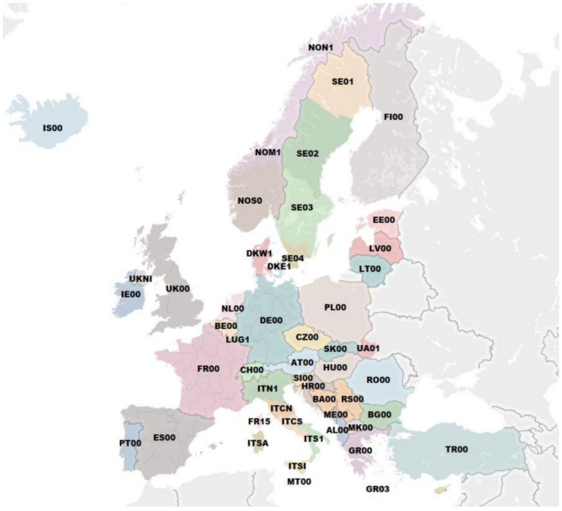


Figure 1.9: Interconnected European power system perimeter [8].

In particular, this association operates evaluating the power system's available sources and the projected electricity demand in order to identify possible issues in the supply and demand mismatch.

Electricity is produced transforming the energy from primary sources into electricity. In Italy, this production relies both on fossil fuels, such as natural gas, oil and coal, and on the renewable energy sources, whose share is constantly increasing, such as geothermal, hydroelectric, solar and wind energy. Nevertheless, in order to guarantee the necessary electricity supply, Italy purchase the electricity also from other countries through 25 interconnections, mostly from France and Switzerland [9].

The gross annual production in 2021 was 289.1 TWh, 3% higher compared to 2020. In particular, the 59.0% of the total domestic production was covered by non-renewable thermoelectric production, the 16.4% by hydroelectric production and the 14.6% by wind, photovoltaic, geothermal and bioenergy. Considering the thermoelectric production, it is possible to appreciate that cogeneration plants represent the 53.7% of the total thermoelectric in 2021, producing 101.6 TWh of electricity and 57.7 TWh of thermal energy (figure 1.10.

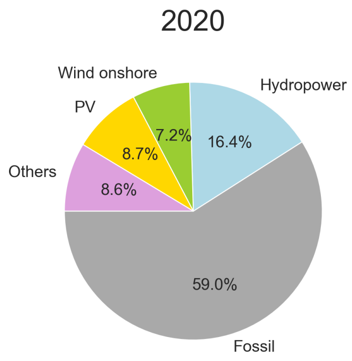


Figure 1.10: Electricity production at 2020 and 2021 [9].

Nowadays, the electricity production relies on a specific power capacity installed mix. It is composed by different type of power plants, using both fossil and renewable sources. In particular, in 2021 the total gross power capacity installed was equal to 119.91 GW, composed by (figure 1.11:

- Hydroelectricity capacity of 19.17 GW.
- Thermo-electricity capacity, which is composed by traditional (61.93 GW) and geo-thermoelectric (0.8171 GW) power plant, equal to 62.75 GW.
- Wind capacity of 11.29 GW.
- Photovoltaic capacity of 22.59 GW.

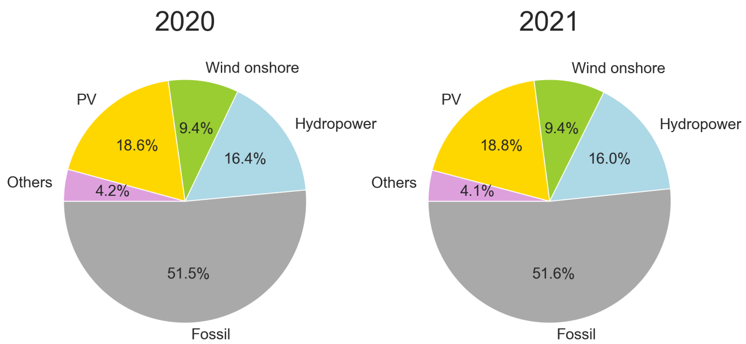


Figure 1.11: Capacity installed by 2020 and 2021 comparison [9].

As shown in the figures 1.10 and 1.11, the higher share of installed capacity is represented by fossil power plant, which rely on fossil sources such as coal, oil, natural gas and non renewable waste. Moreover, in 2021 which is the reference year for this case study, the 48.3% of the capacity installed is composed by renewable plants, such as photovoltaic, wind onshore, hydro-power plants, biomass and renewable waste plants, which are shown as the others.

1.5 Renewable energy technology

1.5.1 Photovoltaic energy systems

Photovoltaic technology aims to directly produce electricity exploiting the Sun rays energy. By means of several photovoltaic modules and panels it is possible to form utility-scale power plants.
The physical principle of this technology is the electrons ability to pass from the valence to the conduction band. This phenomena is possible in conductor materials, where there is no the band gap, and in the semiconductors, there electrons can move in specific conditions. Indeed, in semiconductors material, it is possible to excite the electrons by giving energy in form of photons, and thus creating vacancies in the valence band. The amount of vacancies coincides with the one of the electrons. However, in the energetic field, "doped" semiconductors materials are used, adding an element, therefore an impurity, in order to increase the number electrons with respect to the number of vacancies (type n) or viceversa (type p). Type n impurities are atoms from the fifth group, having 5 valence electrons, while type p impurities are atoms from the third group, with 3 valence electrons.

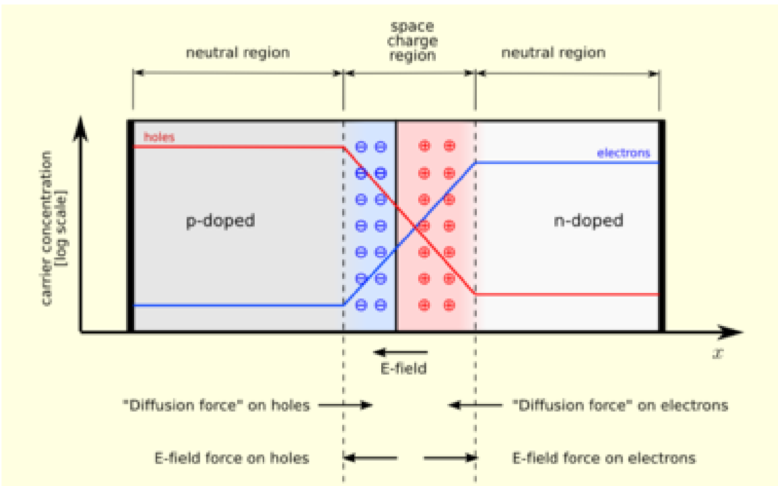


Figure 1.12: P-n junction with electric field.

In the Silicon n-type material, i.e. with Phosphorus, impurity atoms have an extra electrons in the valence band with respect to the necessary amount of electrons for the Silicon bonding: a negative charge is formed. In the Silicon p-type material, i.e. with Boron, impurity atoms miss one electron with respect to the necessary in order to form the bond with Silicon, thus a vacancy exceeds: a positive charge is formed. Therefore, the p-n junction is the union of those two layers (figure 1.12): once they are united there is an electrons migrations from the n-type crystal toward the p-type, and viceversa with the vacancies: the diffusion current is formed. Then, an electrostatic equilibrium state is reached resulting in a negative surplus of charge on the p-type crystal and a positive on the n-type crystal. The intermediate zone between the junction is the depletion region, with no mobile carriers. Moreover, at the junction a potential difference is formed, creating and electric field from n- to p- type crystal.

Then, the electric field determines another electrons and vacancies migration respectively towards n- and p- type crystal, creating an opposite current with respect to the diffusion one. The total result of those two currents is null, because they are equal in module but opposite in orientation.
Nevertheless, if an external potential is applied to the junction, both vacancies and electrons are moved toward the junction, forming the diode current.

Subsequently, if photons hit the p-n junction, the photovoltaic effect is generated. Therefore, the couple electron-vacancy is formed, due to the photons energy absorption: electron is moved toward the n-type crystal and the vacancy toward the p-type. A direct current is generated from the n-type layer toward the p-type, opposed to the diode current. The p-n junction behaves as a direct current generator.

Nowadays, the main three categories are the monocrystalline Silicon (m-Si), polycrystalline Silicon (p-Si) and thin film technologies. The spectral response of the photovoltaic panel depends on the specific commercial technology.
Besides, the available current density J depends on the incident radiation, thus the solar spectrum g(λ), and on the spectral response S(λ) of the crystalline Silicon (figures 1.13 and 1.14):

$$G = \int g(\lambda) d\lambda \tag{1.1}$$

$$J = \int g(\lambda) S(\lambda) d(\lambda) \tag{1.2}$$

In the solar spectrum, only photons with a sufficient energy amount are able to generate the photovoltaic effect, thus the electron-hole pairs. Besides, photons in the visible range and above the ultraviolet have a surplus of energy with respect to the necessary, thus it is lost in the electron-hole generation, representing a limit in the conversion efficiency.

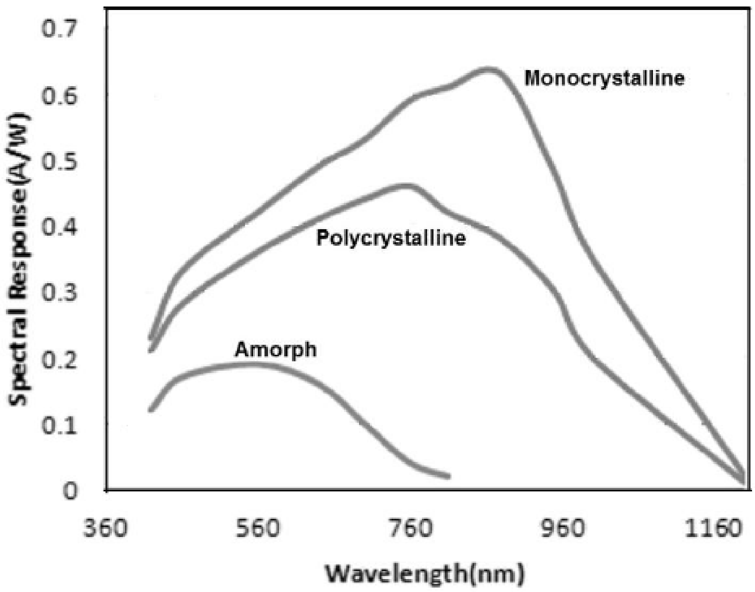


Figure 1.13: PV panel spectral response.

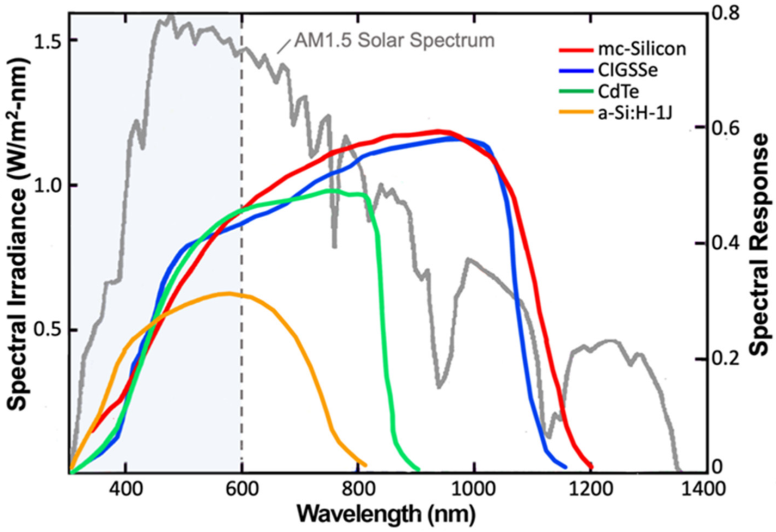


Figure 1.14: Solar irradiance vs PV panel spectral response.

Additionally, there are other conditions affecting the solar cells efficiency:

- part of the incident photons are reflected and vanished in the frontal contact
- some electron-hole pairs recombine themselves before being separated by the electric field inside the junction
- frontal electrode resistance
- imperfect electric isolation

Nevertheless, there are other condition influencing the conversion efficiency such as the tilt of the panel, wind speed, panel temperature, solar spectrum variation and meteorological conditions.
Finally, it is possible to identify two main types of photovoltaic systems:

- Grid connected plants, also with storage system and bidirectional counter to inject or withdraw current from the electricity grid.
- Stand-alone plants, with no grid connection and thus equipped with a storage system.

1.5.1.1 Photovoltaic power plants in Italy

Italy is characterized by a solar source allover the nation, with a direct normal irradiation (DNI) which can reach 5.18 kWh/m2 with e correspondent maximum specific power output equal to 4.54 kWh/kWp [10]. Most of the solar source is concentrated in the Southern regions, as shown in the figure 1.15 and 1.16. The final electricity demand is covered by 9% photovoltaic production, representing the higher share of all the renewable systems exploited in Italy, equal to 21% [9].

Utility-scale photovoltaic power plants are installed in Italy, amounting for 23 GW of installed capacity. In particular, 97.6% of PV plants are connected to the low voltage distribution grid; 2.4% are connected to the medium voltage grid representing the 55% of the total capacity, and only a small number of plants are connected to the high voltage grid. Besides, 44.5% of the total capacity installed is located in the North and 37.4% in the South. Apulia region has the higher amount of installed capacity [11].

Figure 1.15: Direct normal irradiation map for Italy [10].

Figure 1.16: Photovoltaic power potential map for Italy [10].

Figure 1.17: Photovoltaic GW map [9].

In figure 1.17, photovoltaic power plants concentration is shown for each Italian region [9]. The main technology used is the polycristalline Silicon modules, while thin film technology is mainly used in the South, especially in Silily. Valle d'Aosta and Bolzano province regions have the higher share of monocrystalline modules.

1.5.2 Wind onshore and offshore energy systems

1.5.2.1 Wind source

Wind source is the air movement, due to the unbalance of heating of the Earth by the sun and the Earth rotation (figure 1.18). Indeed, across the globe. there is a temperature variation which cause the global circulation. Sun rays are the main source of heat, which interact with different subjects: they are partially absorbed by clouds, atmospheric gases and Earth surface. Besides, some parts of the Earth receive more radiation energy than others, due to the Earth curvature: at high latitude, the radiation is spread over a much larger area, while at the equator the same amount of energy is more concentrated. Closer to the Poles, the radiation crosses a thicker atmosphere in comparison to the Equator, thus more radiation is lost due to the interactions such as scattering and absorption by gases and particles. Moreover, the Earth inclination determines a scarcer sun exposition of Poles, which during the winter do not receive any sunlight. In the Poles, the combination of ice, snow and thick clouds determines a reflection of the radiation which is sent back into the space. The albedo factor, which represent the reflectivity, is important in determining the actual sun radiation hitting the surface and thus heating up the Earth. Therefore the combination of those different phenomena determine a thermal gradient between the Equator and the Poles: at 40° pole-wards latitude, the outgoing heat radiation from the Earth exceeds the incoming heat from the Sun.

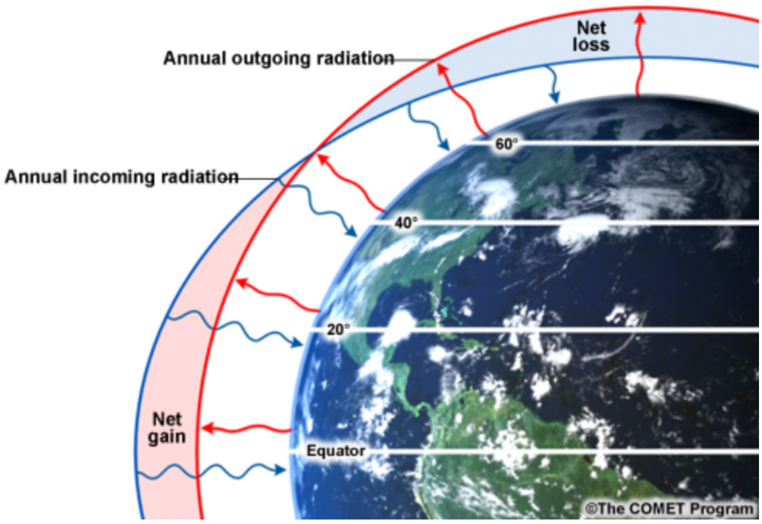


Figure 1.18: Earth radiation balance [12].

Therefore, the global circulation (figure 1.19) redistributes the heat, avoiding the Equator overheating and the Poles freezing. This circulation is due to three large atmospheric cells, which are the Hadley, Ferrel and Polar cells, which are present both in the northern and southern hemispheres. The Hardley cells are the largest one, warmer at the equator where the less dense air rises. Then, Polar cells are the smallest, characterized by colder and thus less dense air. Finally, Ferrel cells are in between the previous cells on which these cells depend, and are not driven by the temperature but act as permanent areas of high and low pressure, due to the rising and descending parts of the circulation cells.

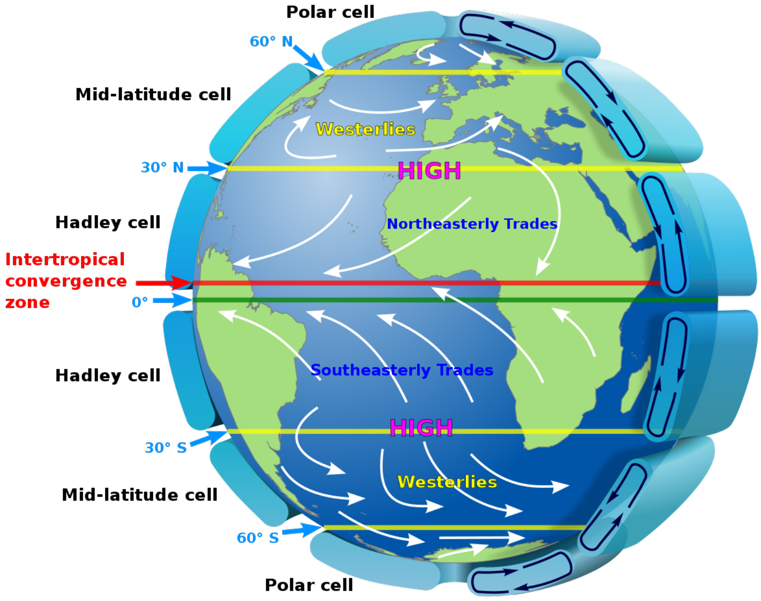


Figure 1.19: Global circulation [13].

Moreover, the global circulation pattern in due to the Earth rotation. The spin of the Earth induces an apparent motion to the right in the Northern Hemisphere and to the left in the Southern: this is the Coriolis effect, which is directly caused by the fact that the Earth rotates faster at the Equator with respect to the Poles. As a result, the air does not move in straight line from the Equator to the Poles. To an observer from the ground, air moves in a curved direction without being present any physical force causing this deflection.
At 1000 m altitude above ground level, it is possible to find geostrophic winds, which are theoretical winds resulting from the exact balance between the Coriolis force and the pressure gradient. True winds differ from those due to other factors and forces, such as the friction with the ground. Indeed, the air layer near the ground is affected by the terrain elevation and surface roughness, the diurnal heat and moisture. Besides, the wind gradient, or wind shear, which is the difference in

wind speed or direction over a short distance in the atmosphere, depends on the height and on the terrain and thus there is a direct link between wind speed and altitude. Besides, the wind stream can be classified as turbulent, in which the fluid motion is characterized by a chaotic variation in pressure and velocity, or laminar flow in which the fluid moves in parallel layers. Possible sources of turbulences are the modifying factors, such as orographic and surface roughness variation, and local factors, thus thermal convection, natural and artificial obstacles, terrain steepness and also operating wind turbines. In figure 1.20 artifical and natural obstacles which influence the wind flow are shown.

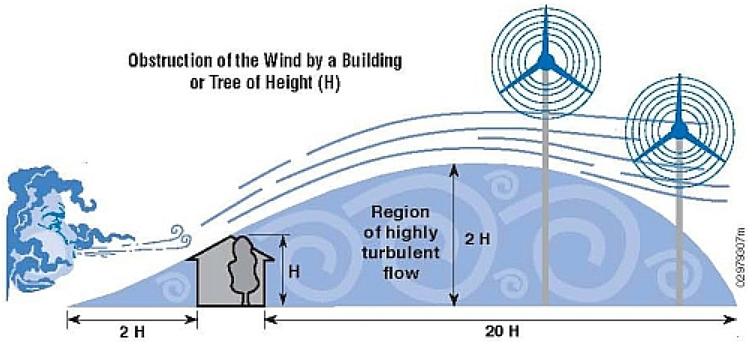


Figure 1.20: Artificial and natural obstacles influencing wind flows [14].

1.5.3 Wind energy extraction

Wind onshore and offshore technologies aim to extract the wind energy directly generating electricity. Indeed, wind energy source is exploited by means of a turbines. In particular, the kinetic energy of the wind flux is equal to:

$$dE = 1/2dmU^2 = 1/2\rho AU^3dt \tag{1.3}$$

and power is the derivative of the energy with respect to time:

$$P = dE/dt = 1/2\rho AU^3 \tag{1.4}$$

therefore, depending on the wind speed (U), mass of air (density ρ) flowing in a specific section and the area of the section itself (A). Nevertheless, the actual extractable power is lower and thus by means of the Betz theory, it is computed as:

$$P = 1/2C\rho AU^3 \tag{1.5}$$

where C_P is the power coefficient depending on the induction factor which consider the wind speed variation due to the pressure drop. The maximum value of C_P is equal to 16/27. Therefore, from the Betz theory, the maximum power it is possible to gain from a wind flow is equal to

$$P = 16/54\rho A U^3 \tag{1.6}$$

However, this theory is based on the modelling of a two-dimensional flow of the rotor. In reality, there is an air wake effect due to the rotor converter which adds a motion spin, opposite to the rotor speed itself. In this way, the final speed residual, after the rotor, is higher and thus a lower energy is gained from the wind flow. Therefore, the turbine power coefficient is smaller than the Betz value.

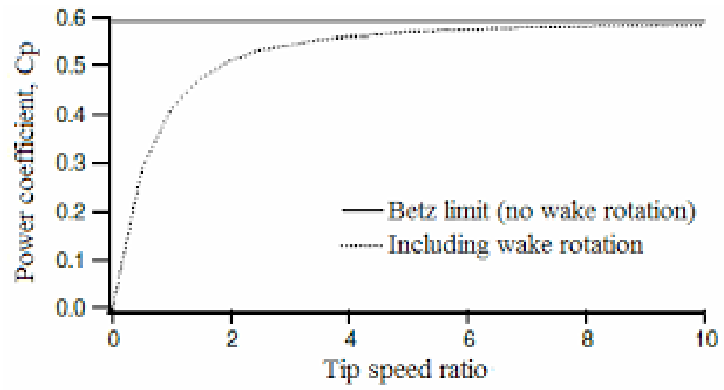


Figure 1.21: Power coefficient Betz theory vs wake rotation.

As shown in the figure 1.21, the C_P can be directly expressed as a function of the tip speed ratio λ, which is the ratio between the tangential velocity at the rotor tip and the wind speed. The higher the tip speed, the higher the power coefficient, which tends to the Betz limit.

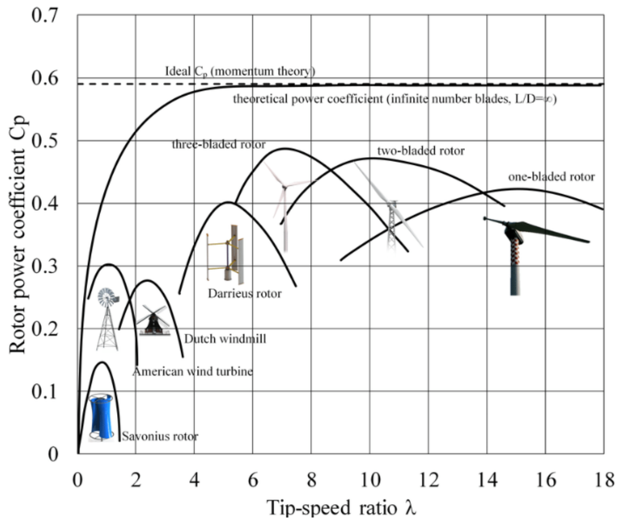


Figure 1.22: Power coefficient of different types of wind turbines.

As shown in the figure 1.22, there are different typology of wind turbine, in particular they are identified in horizontal and vertical axis. Horizontal axis wind turbines (HAWT) are the most used because of the higher efficiency with respect to the other category. However, it is necessary a yaw control, not required for the vertical axis wind turbines, which though are less efficient and more bulky.

1.5.3.1 Onshore wind power plants in Italy

Italy is characterized by onshore wind source especially in the South as shown in figures below, with a mean wind density equal to 7.81 m/s and a power density equal to 784 W/m2 at 150 m for the 10% windiest areas [15]. Apulia region produces one fourth of the national electricity power, it follows Sicily with 18% production, Campania with 14%, Basilicata with 13% and Calabria and Sardinia with 10% together.
Figures 1.23 and 1.24 show the mean wind speed and mean power density at 150 m for Italy [15].

Figure 1.23: Mean wind speed map at 150 m for Italy [15].

The final electricity demand is covered by 7% onshore wind production, representing the 18% share of all the renewable systems exploited in Italy [9]. The final electricity demand is covered by 7% onshore wind production, representing the 18% share of all the renewable systems exploited in Italy [9].

Figure 1.24: Mean power density (right) maps at 150 m for Italy [15].

Figure 1.25: Onshore wind GW map.

1.6 Storage technology

1.6.1 Battery storage

Batteries are electrochemical cells in which the chemical energy is transformed in one step into electrical energy. The main three component are cathode, anode and electrolyte. By means of ions and electrons exchange, reactants and products are exchanged inside the box, constituting the electrodes material.
The base reactions of the working process are oxidation and reduction. Besides, the internal chemistry inside the battery box is not constant, but it evolves during the discharge and charge phase. Electrodes and electrolyte interacts by means of the oxidation reaction negative charges are released and migrate toward the cathode electrode, while with the reduction reaction positive charge are generate and migrate toward the anode electrode.
Additionally, there are several chemistires available: Lead-acid (LA), Nichel-Cadmium (Ni-Cd) and Nichel metal hybrides (NiMH).
In figure 1.26 gravimetric power and energy densities are shown for differen rechargeable batteries. Most of these systems are currently being investigated for grid storage applications [16].

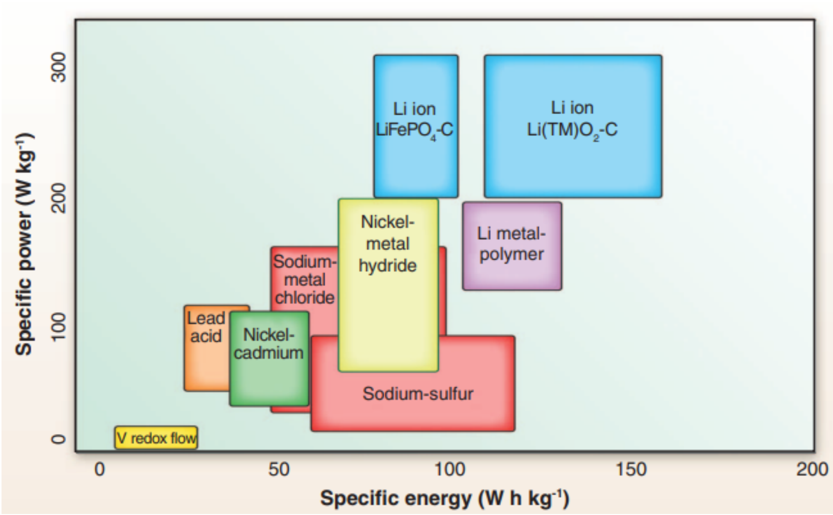


Figure 1.26: Gravimetric power and energy densities for differen rechargeable batteries [16].

There is also the Lithium-ions battery (Li-ion), shown in figure 1.27, which is characterized by an anode composed of graphite matrix containing Li-ions, and the cathode composed by Lithium Cobalt oxide, Lithium manganese oxide or Lithium ion phosphate, depending on the application. In particular, Li-ion batteries are the electrochemical cells considered in this case study, because of their specific characteristics, such as high roundtrip efficiency, low self-discharge rate, wide cycling modulation range and high lifetime [17].

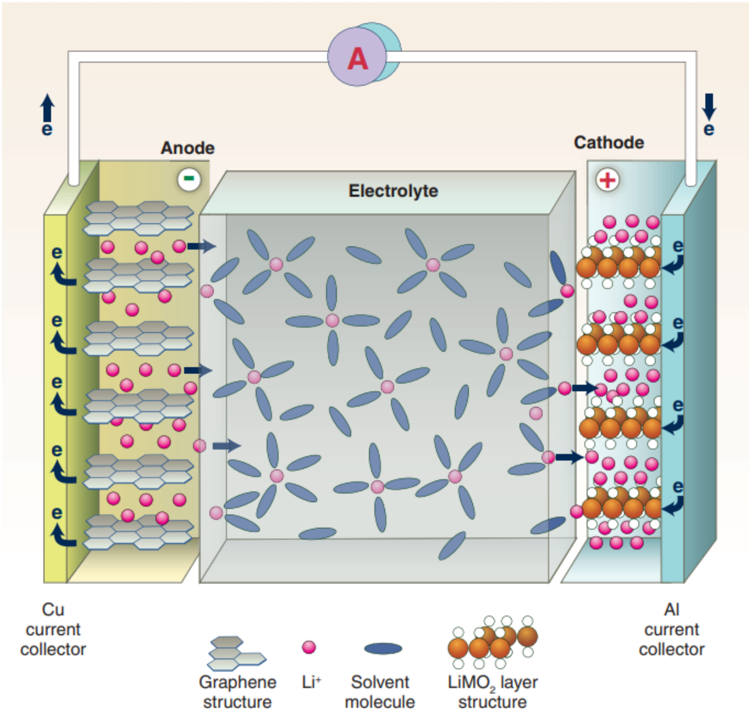


Figure 1.27: Schematic of a LIB [16].

In figure 1.27, it is shown a schematic of Li-ion battery, where the negative electrode is composed by graphitic carbon holding Li-ions inside the layers, while the positive electrode is a oxide Li-intercalation compound often characterized by a layered structure. Both anode and cathode are able to insert and remove Li-ion from their structures and are separated by a nonaqueouse electrolyte able to transport ions. during the charging phase, Li-ions migrated from the oxide compound towards the graphite layers. The opposite happens during the discharging phase [16].

1.6.2 Hydrogen storage

Hydrogen storage is another way to store electricity into chemical energy and then reverse the process. Indeed, hydrogen could play a crucial role in storing the electricity produced by intermittent renewable sources. It can be produced in different ways depending on the material used and on the energy sources, as shown in the figure 1.28.

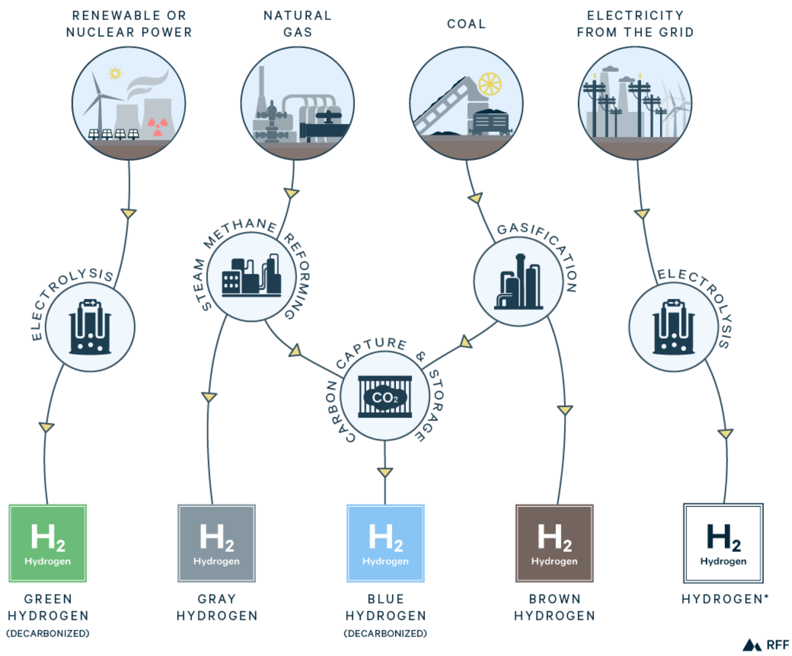


Figure 1.28: Hydrogen color scale [18].

The main processes are [18]:

- Gray hydrogen: it is produced from natural gas, which is a fossil fuel, by means of an endothermic process, by means of steam methane reforming plants.
- Blue hydrogen: it is produced with the same process and fuel of gray hydrogen but adding the CO_2 removal.
- Brown hydrogen: it is produced using coal and by means of a gassification process, which is expensive and inefficient.
- White hydrogen: it is produced using the grid electricity, which can be both green or fossil, depending on the electricity origin.

- Green hydrogen: it is produced from water and biomass using several processes step. In particular, starting from water and using renwable sources, such as photovoltain, onshore and offshore wind and hydropower, but also with nuclear source by means of the electrolisys process hydrogen can be produced.
- Turquoise hydrogen: it is produced by means of biogas pyrolysis, obtaining carbon in solid form and hydrogen.

Hydrogen storage is composed by three main components: electrolyzer, fuel cell and hydrogen tank.

Electrolyzers are able to convert electricity into molecular hydrogen. Then hydrogen can be transformed again into electricity by means of fuel cells. Besides, both electrolyzers and fuel cells working principle relies on reduction and oxidation reactions. Starting from water molecules,it is used electricity to split those molecules intro hydrogen and oxygen, which is re-transformed into electricity with the opposite reaction.

In particular, there are different typologies of electrolyzers, such as Proton-Exchange Membrane (PEM), alakaline (AWE) and Solid Oxide electrolysis cells (SOEC). AWE technology is able to produced a low voltage at the electrodes and it is characterized by poor performance, due to high ohmic drop. SOEC technology shows a dynamic behaviour, it produces high quality hydrogen and has high efficiency thanks to the high temperature process, though is is not suitable for start-stop operation. Therefore, in this case study, it is considered a PEM electrolyzers (figure 1.29) for the hydrogen production because of the excellent dynamic behaviour and thus their compatibility with the VRES.

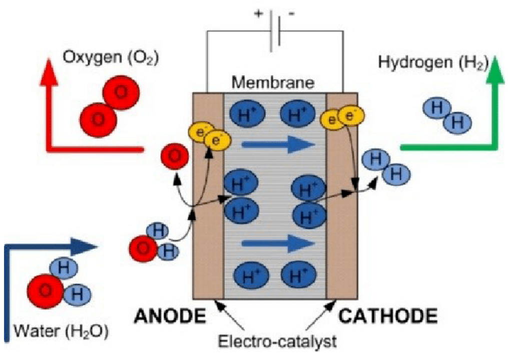


Figure 1.29: PEM electrolyzer reaction schematic [19].

Indeed, this kind of electrolyzers are characterized by response based on thew dynamic current profiles. Responses are directly linked with the operating conditions and PERM electrolyzers responds immediately. Therefore, they are perfectly suitable for VRES since they are dynamic sources which operation strongly depends on the weather conditions [20].

Fuel cell is able to convert hydrogen back to the electricity form. It is an open electrochemical cell, where reactants come from the external environment while products are rejected towards the environment. The different fuel cells technologies are the Solid Oxide fuel cell (SOFC), Molten Carbonate fuel cell (MCFC), Phosphoric Acid fuel cell (FAFC) and Proton-Exchange Membrane fuel cell (PEMFC). The most suitable fuel cell technology to be coupled with RES is the PEMFC (figure 1.30), due to its high dynamic and fast response.

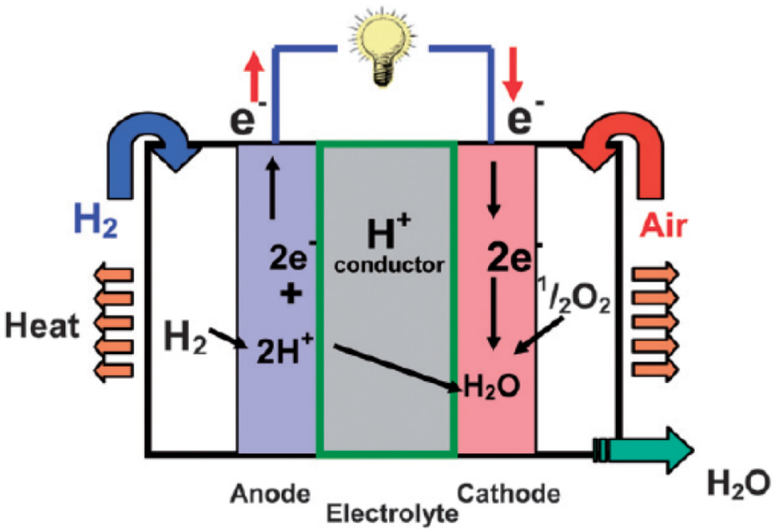


Figure 1.30: Operating principles of a PEMFC [21].

1.6.3 Power-to-Power concept

Power-to-Power (P2P) system are a combination of technology which is necessary to face and overcome some issues and limitation of the increasing renewable electricity production and storage [22]. Indeed, the higher use of non-dispatchable renewable sources determines new challenges to the electricity infrastructure which require a higher flexibility in balancing power supply and demand. There are different strategies in order to deal with this issue, such as flexible generation, energy storage ans demand side response. However, grid flexibility can be generated by means of electricity conversion into other energy commodities, such as hydrogen. In this case study, electricity is produced and by means of the elctrolyzers it is stored into chemical energy form, producing hydrogen molecules. Then, hydrogen is re-transformed into electricity by means of fuel cells. therefore, the hole electricity system is composed by electricity generator technologies, electrolyzers, fuel cells, batteries which support the system and the daily energy buffer.
In figure 1.31 the P2P scheme applied for this work is shown.

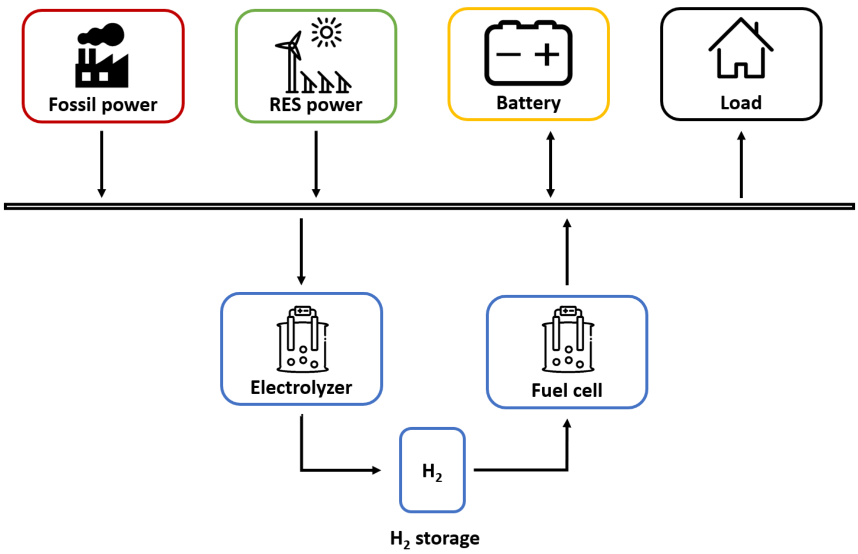


Figure 1.31: P2P energy system scheme.

Chapter 2

Model definition

The energy system analysis is done considering a modelling approach in order to investigate the actual energy situation and to make forecasts for the future. Nowadays, there are different energy systems models, but they often require significant investments in terms of human resources training and software purchase in order to apply or further develop them. They are also difficult to be integrated with other possible tools [23]. Nevertheless, the use of modelling tool is essential in order to face the recent years requests. In particular, there is a huge effort to find the best solution in order to meet the increasing energy demand but also considering the different policies and constraints due to the actual critical climate change issue.

2.0.1 Energy system model

Modern energy systems are built considering the overall interactions between energy supply, distributors and demand. In order to provide accurate predictions and enable informed energy system design, implementation and operation decision, it is necessary to use high quality data and tools. There are three key conditions that should be met: (1) models have to be appropriate with respect to the target environment, (2) suitable data must be used as input of the model, (3) model must be used by experts in order to properly understand the outcomes.

Energy model can be identified in two different categories: bottom-up and top-down energy models. In particular, a top-down energy model aims to define the economy of specific regions and to estimate the effects of energy policies in monetary units. On the other side, a bottom-up energy model is characterized by a high degree of technological details, but is not able to consider the macroeconomic impacts of any energy policy [24].

In general, energy system optimization models (ESOMs) are used to provide awareness to make decisions regarding issues related to the climate and energy policy at different scale. These models are able to give a global representation of the whole energy system analysing the energy dynamics over a long-term period. They are characterized by a base typical scheme (figure 2.1), which is composed by the inputs (energy supply, energy demand, economic parameters) and by outputs.

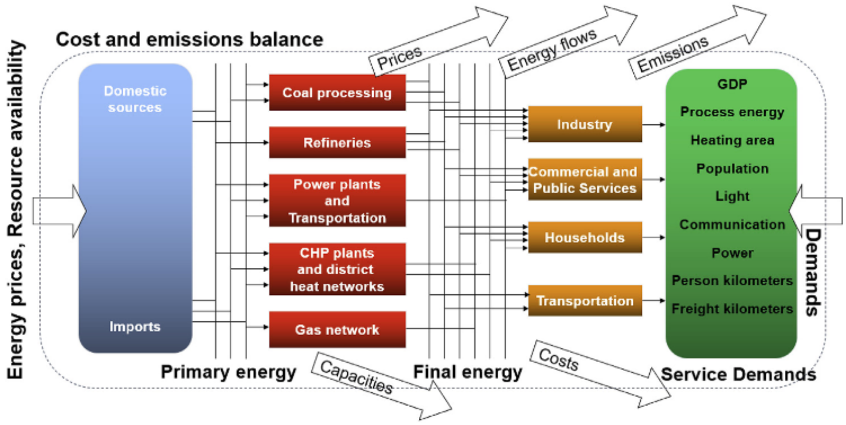


Figure 2.1: Schematic of TIMES model [25].

One of the most used ESOM model is the MARKAL/TIMES family models developed by the Energy Technology Systems Analysis ORigramme (ETSAP) under the International Energy Agency (IEA) since 1970. Other ESOMs models include MESSAGE, ESME, OSeMOSYS and TEMOA.

The TIMES (The integrated MARKAL-EFOM System) model generator combines two different approches, the technical engineering and the economic one. It is a technology rich, bottom-up model generator based on a linear programming to elaborate a least-cost energy system optimized with respect to the constraints, over a medium- long- term scenario [26].

The energy supply model MESSAGE (Model for Energy Supply Systems And their General Environmental impact) is a dynamic linear programming (DLP) model which minimizes the total discounted costs of energy supply over a time horizon. The main objective is the balancing of demand for the final energy and supply of primary commodities by means of different technologies [27].

The ESME (Energy System Modelling Environment) is based on a policy-neutral cost optimization. It finds the least cost energy systems designs which is able to meet the imposed sustainability and security targets [28].

The TEMOA (Energy Model Optimization and Analysis) is an open source in order to elaborate energy systems analysis. It is based on an energy economy optimization (EEO) model, minimizing the present cost of the energy supply by optimizing the energy technologies use over a specific time horizon [29].

The OSeMOSYS (Open Source energy Modelling System) is designed as a tool to analyse the development of energy strategies at local, national and multi-regional level. It is a deterministic, linear optimization long-term modeling framework, based on the optimization of the net present value cost of the energy system [30].

By means of these kind of models it is possible to built projections to 50 or 100 years in the future, leading to unavoidable uncertainties. The uncertainties are categorized in parametric, due to the lack of knowledge about the model parameters, and structural, due to the uncertainties in the model equations. The main feature of ESOMs is that they tend to use scenarios to handle uncertainties or treat them as a marginal issue, avoiding a limited not robust model, which could lead to not suitable decisions for the future [25].

2.0.2 OSeMOSYS modelling framework

For this case study, it is chosen as energy system model the OSeMOSYS (Open Source Energy Modeling System) tool. It is full-fledged system optimization model for long-run energy planning. In particular, it is a deterministic, linear optimization, long-term modeling framework. It is also possible to apply mixed-integer linear programming for specific functions.

Moreover, it is characterized by a extensive definition of both technology and energy vector. It is designed in order to easily allow updates and modifications to suit the needs of a specific analysis. In order to do so, the model is developed in a series of component blocks of functionality (figure 2.2): objective (1), costs (2), storage (3), capacity adequacy (4), energy balance (5), constraints (6) and emissions (7). Each block is also divided into different levels of abstractions, such as the plain English description of the model, the algebraic formulation of the plain English description, the implementation of the model in a programming language and the application of the model, which depends on how it is used [23].

Those blocks are characterized by different features:

1. Objective: the objective of the model is the minimization of the net present value (NPV) cost of the energy system to meet the energy demand.

2. Costs: they are considered for each technology, in each year and in each region modeled. Operating, investment costs, possible emission production penalties and also salvage costs are considered.

3. Capacity adequacy: it is due to the fact that must be enough capacity of a specific technology in order to meet its energy use or production requirements.

4. Energy balance: the production, use and demand for a fuel or a specific service have to be feasible at each time slice and annually.

5. Constraints: it is possible to have maximum and minimum limit on the total capacity of a specific technology.

6. Emissions: it is due to the fact that a technology activity can have an impact on the environment.

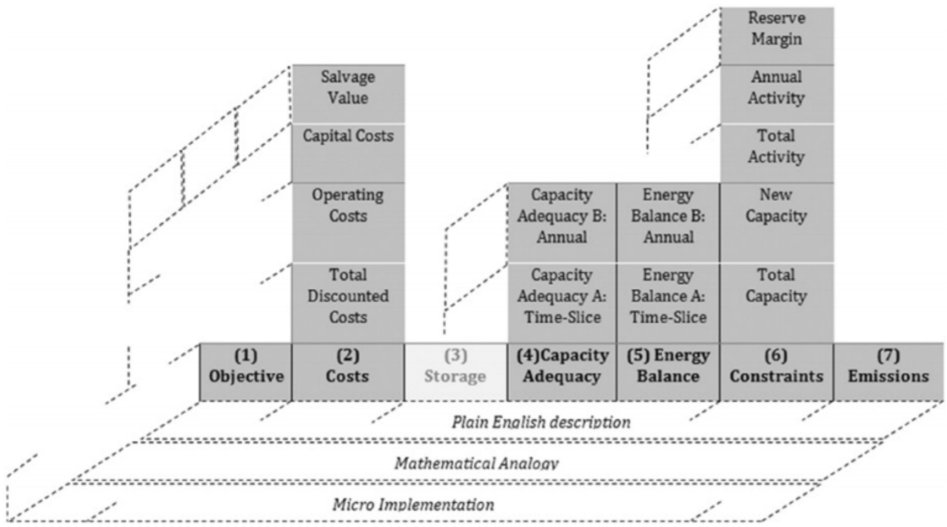


Figure 2.2: Current OSeMOSYS blocks and levels of abstraction [23].

In order to elaborate a long-term model, the following key parameters are considered:

- Sets: to define the physical structure of the model.
- Parameters: input of the model.
- Variables: as outputs of the model.

Finally, the structure of the energy system is based on different features:

- Regions: areas in which the energy balance is ensured.
- Fuel: energy vectors.
- Technologies: which transform, extract, import and export energy vectors.
- Storages: which accumulate fuels over different time periods.

2.1 Reference Energy System

The Reference Energy System is a graphic abstraction of the energy system to be modelled. In particular, it is the first data elaboration step, in order to identify which are the mains determining the whole energy system. This base scheme is composed by energy commodities, which are indicated with vertical lines, energy flows, which are indicated with horizontal lines, and technologies, which are indicated as boxes. In order to elaborate the whole Italian electricity flux, from its primary energy supply to the final demand, it is used the Italian Energy flow diagram [31], shown in figures 2.3 and 2.4.

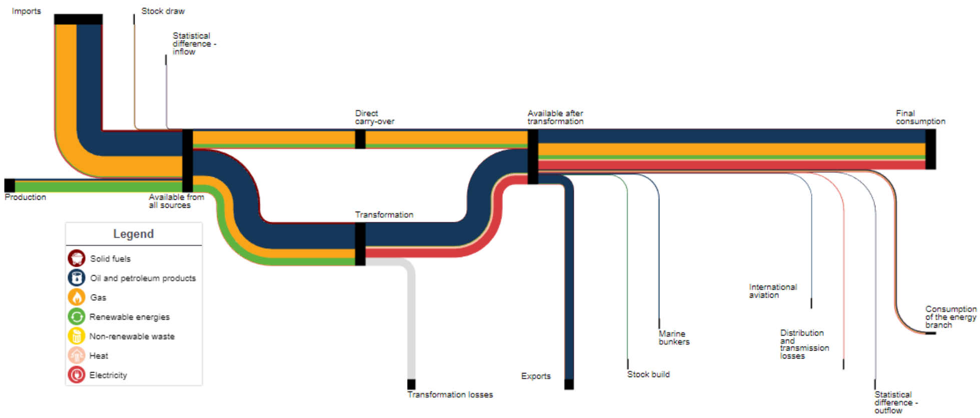


Figure 2.3: Italian Energy flow diagram from Eurostat [31].

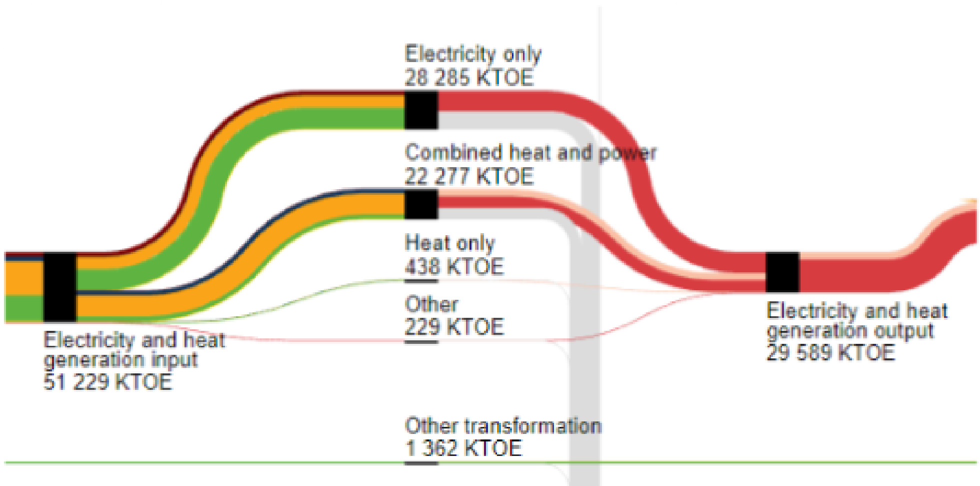
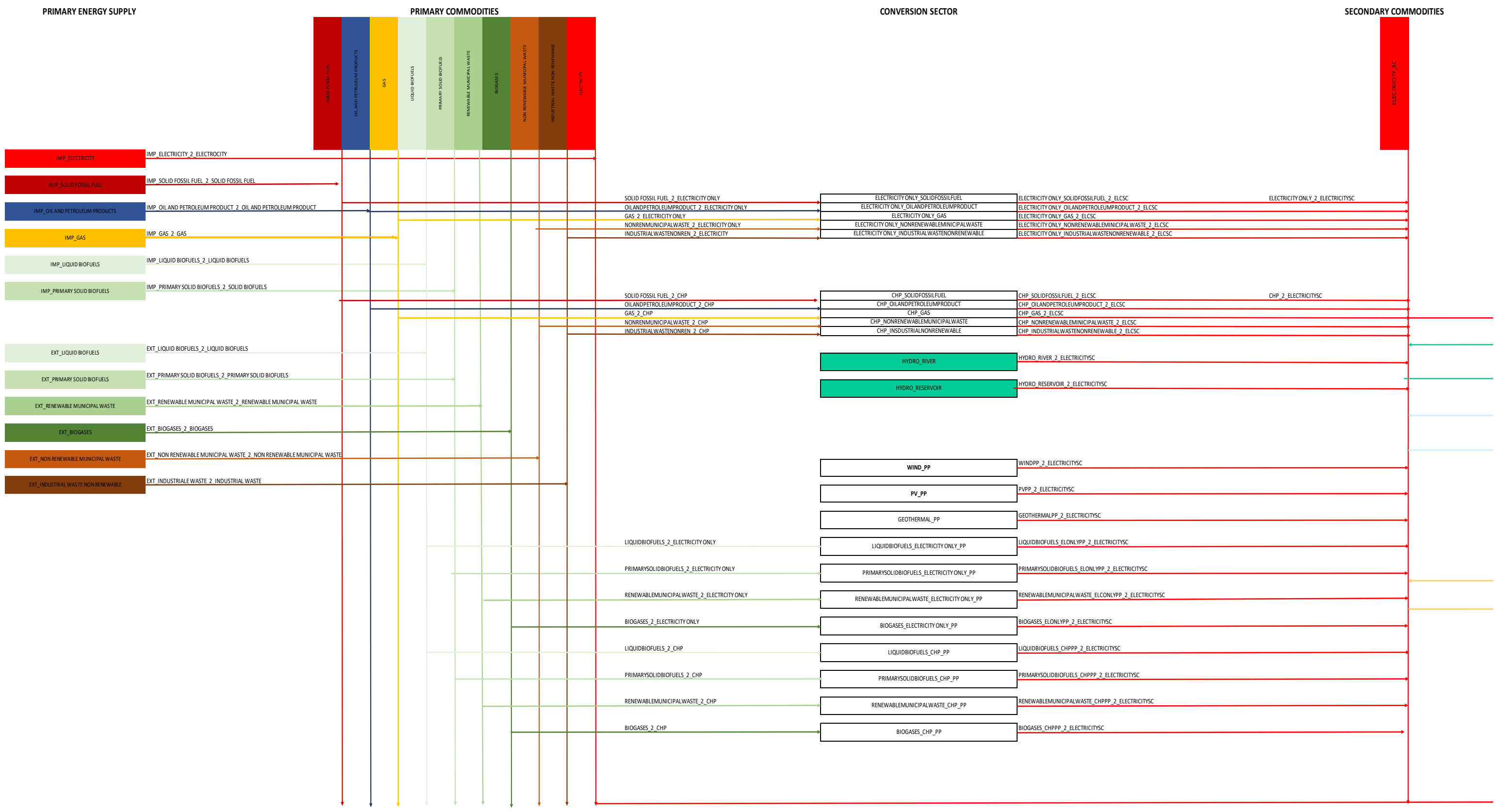


Figure 2.4: Italian Electricity production flow diagram from Eurostat [31].

In this case study it is considered the whole Italian electricity sectors divided as it follows:

- Primary energy supply: imports and extractions of primary commodities.
- Primary commodities.
- Conversion sectors.
- Secondary commodities: it is composed only by the electricity commodity, derived from the different production technologies.
- Distribution: it is made by the electricity distribution
- Final demand



PRIMARY ENERGY SUPPLY
PRIMARY COMMODITIES
CONVERSION SECTOR
SECONDARY COMMODITIES
SOLID FOSSIL FUEL
OIL AND PETRULEUM PRODUCTS
GAS
LIQUID BIOFUELS
PRIMARY SOLID BIOFUELS
RENEWABLE MUNICIPAL WASTE
BIOGASES
NON RENEWABLE MUNICIPAL WASTE
INDUSTRIAL WASTE NON RENEWABLE
ELECTRICITY
ELECTRICITY_SC
IMP_ELECTRICITY
IMP_ELECTRICITY_2_ELECTROCITY
IMP_SOLID FOSSIL FUEL
IMP_SOLID FOSSIL FUEL_2_SOLID FOSSIL FUEL
IMP_OIL AND PETROLEUM PRODUCTS
IMP_OIL AND PETROLEUM PRODUCT_2_OIL AND PETROLEUM PRODUCT
IMP_GAS
IMP_GAS_2_GAS
IMP_LIQUID BIOFUELS
IMP_LIQUID BIOFUELS_2_LIQUID BIOFUELS
IMP_PRIMARY SOLID BIOFUELS
IMP_PRIMARY SOLID BIOFUELS_2_SOLID BIOFUELS
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EXT_BIOGASES_2_BIOGASES
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EXT_NON RENEWABLE MUNICIPAL WASTE_2_NON RENEWABLE MUNICIPAL WASTE
EXT_INDUSTRIAL WASTE NON RENEWABLE
EXT_INDUSTRIALE WASTE_2_INDUSTRIAL WASTE
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OILANDPETROLEUMPRODUCT_2_ELECTRICITY ONLY
GAS_2_ELECTRICITY ONLY
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OILANDPETROLEUMPRODUCT_2_CHP
GAS_2_CHP
NONRENMUNICIPALWASTE_2_CHP
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CHP_INSDUSTRIALNONRENEWABLE
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HYDRO_RESERVOIR_2_ELECTRICITYSC
WIND_PP
WINDPP_2_ELECTRICITYSC
PV_PP
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PRIMARYSOLIDBIOFUELS_2_ELECTRICITY ONLY
PRIMARYSOLIDBIOFUELS_ELECTRICITY ONLY_PP
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RENEWABLEMUNICIPALWASTE_ELECTRICITY ONLY_PP
RENEWABLEMUNICIPALWASTE_ELCONLYPP_2_ELECTRICITYSC
BIOGASES_2_ELECTRICITY ONLY
BIOGASES_ELECTRICITY ONLY_PP
BIOGASES_ELONLYPP_2_ELECTRICITYSC
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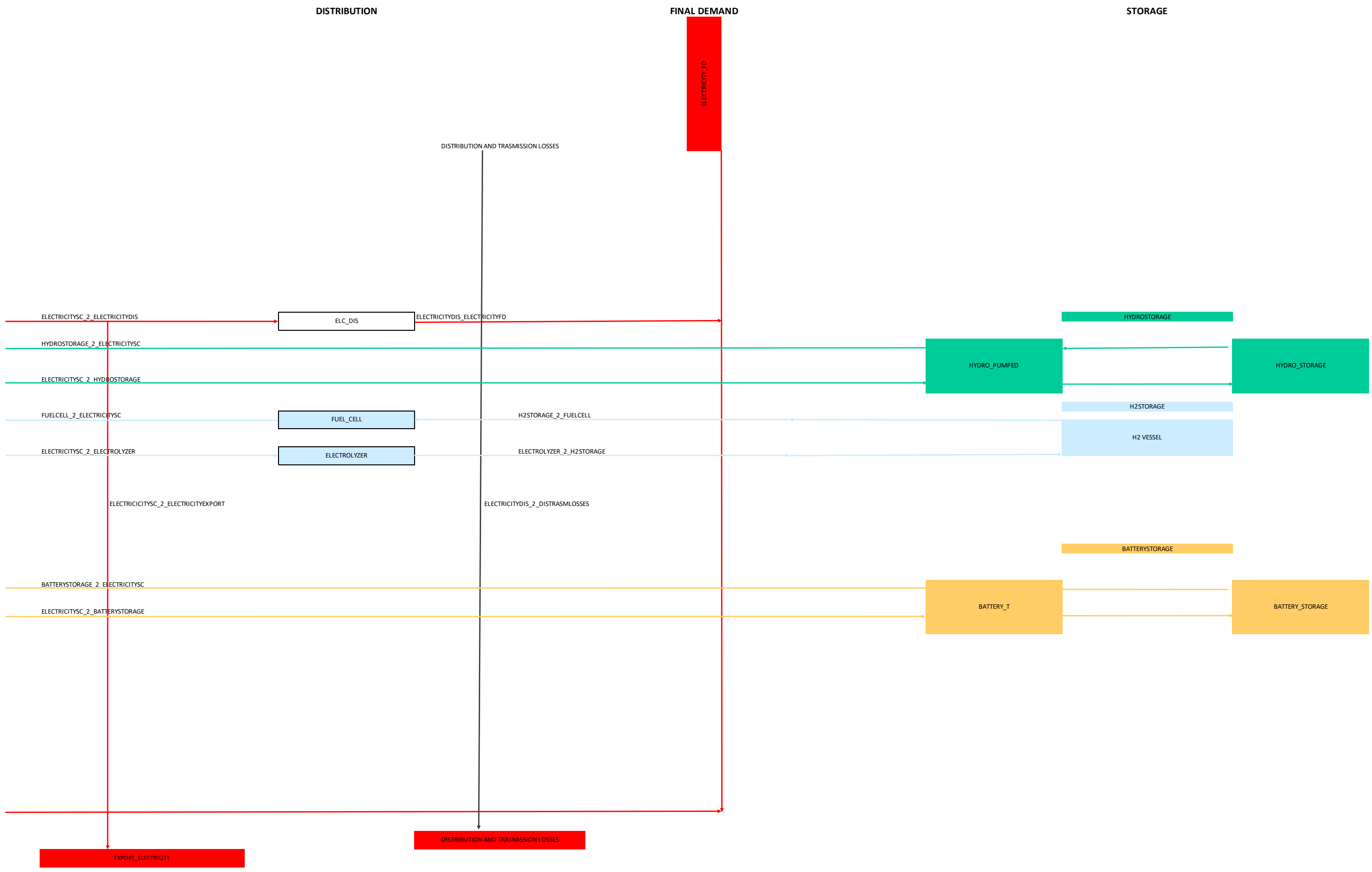
DISTRIBUTION
FINAL DEMAND
STORAGE
ELECTRICITY_FD
DISTRIBUTION AND TRASMISSION LOSSES
ELECTRICITYSC_2_ELECTRICITYDIS
ELC_DIS
ELECTRICITYDIS_ELECTRICITYFD
HYDROSTORAGE
HYDROSTORAGE_2_ELECTRICITYSC
HYDRO_PUMPED
HYDRO_STORAGE
ELECTRICITYSC_2_HYDROSTORAGE
H2STORAGE
FUELCELL_2_ELECTRICITYSC
FUEL_CELL
H2STORAGE_2_FUELCELL
H2 VESSEL
ELECTRICITYSC_2_ELECTROLYZER
ELECTROLYZER
ELECTROLYZER_2_H2STORAGE
ELECTRICICITYSC_2_ELECTRICITYEXPORT
ELECTRICITYDIS_2_DISTRASMLOSSES
BATTERYSTORAGE
BATTERYSTORAGE_2_ELECTRICITYSC
BATTERY_T
BATTERY_STORAGE
ELECTRICITYSC_2_BATTERYSTORAGE
DISTRIBUTION AND TRASMISSION LOSSES
EXPORT_ELECTRICITY

The conversion sector considers the different technologies currently used in Italy for the electricity production and it is mainly composed by the direct fossil fuel electricity production (EL), combined heat and power production (CHP) and renewable power plants.

Both the traditional power plants for direct electricity production and the combined power plants are fed with different fossil fuels, such as the coal and other solid compounds (COAL), oil and other petroleum products (OIL), natural gas (GAS), non renewable municipal waste (NONREN_MUNWASTE) and non renewable industrial waste (NONREN_INDUWASTE).

In addition, also renewable power plants are considered, such as hydro-power plants and its different typologies (HYDRO_RESERVOIR_PP, HYDRO_ROR_PP, HYDRO_PUMPED), on-shore wind power plant (WIND_PP), photovoltaic power plant (PV_PP), geothermal power plant (GEOTHERMAL_PP) and bioenergies power plants diversified for the type of biomass and for electricity only production and combined heat and power production (LIQUIDBIOFUELS_EL, PRIMARYSOLIDBIOFUELS_EL, RENEWABLEMUNICIPALWASTE_, BIOGASES_EL, LIQUIDBIOFUELS_CHP, PRIMARYSOLIDBIOFUELS_CHP, RENEWABLEMUNICIPALWASTE_CHP, BIOGASES_CHP).

Moreover, also the three storages systems are considered in the energy system analysis. In particular, hydrostorage, which is nowadays already used in Italy, battery storage and hydrogen storage. Each storage technology is divided into two components: the power and the energy component. Therefore, the battery technology (BATTERY_TECH), electrolyzer (ELY) and fuel cell (FC) are the technologies associated to the storage, while the battery storage (BATTERY_STORAGE) and the hydrogen tank (HY_TANK) are the storages associated for the charging and discharging. In particular, for the battery technology, it is considered the Li-ion battery due to its high roundtrip efficiency, low self-discharge rate and wide cycling modulation range [17]. The hydrogen tank is assumed as a pressurezed vessel.

2.2 Model parameters definition

The next step in order to build the model is the definition of different parameters and simplification assumptions in order to prepare the input data complex. In particular, it is necessary to define the units of measurement, the time slice division, the economic parameters and finally the technical parameters.

2.2.1 Data and choises of units

The input data definition is a main step in order to have proper and feasible model results. It is important to chose accurate data and make proper assumption in order to have a more representative understanding of the energy system. The typical data required are the following:

- Energy demand
- Technology specific features
- Technology and fuel costs
- Resource potential
- Emissions

Moreover, for OSeMOSYS there are four units related to the input variables (figure 2.5), which are energy, power, cost and emission, and it is necessary to chose those units in a consistent manner.

Input variables	Possible choice of unit
Energy	GWh, MWh, PJ, GJ, etc.
Power	GW, MW, etc.
Cost	Million $, Million £, Million Euro, etc.
Emission	Mton

Figure 2.5: Possible units of measurements in OSeMOSYS [30].

In particular, there is no unit conversion in OSeMOSYS, thus it is assumed that all units are consistent and coherent. In this case study, it is chosen to use GW as unit of measurement for the power and GWh as unit of measurement for the energy. Therefore, the parameter *CapacityToActivityUnit* is set equal to 8760 GWh/GW for each technology producing the electricity commodity, while it is set equal to 1 for the others, such as import and extraction of primary commodities.

2.2.2 Time slices

The importance of representing time-varying input data in energy systems models is strictly related to the renewable energy sources time variation. In particular, the use of time series aggregation (TSA) allows a reduction of the complexity of the model, showing a direct influence on the optimization models.

Therefore, the main challenge in energy system optimization problems is the temporal fidelity, due to the fact that electric system operations depend intimately on second to sub-second alignment of the supply and demand, on hourly- and daily-scale dispatch and bidding decisions, and on decade-scale investments decisions. The temporal resolution data affects the optimal investment solutions, due to renewable energy availability which varies with time and is an input of the model [32].
Typically, long-term energy models use a coarse time series in order to limit the computational effort. Thus, they are characterized by a rigid representation of the time series (figure 2.6), based on the typical periods (time slices) which are obtained considering each *year (y)* composed by the sequence of *seasons (ls)*, *daytypes (ld)* and *dailytimebrackets (lh)* [33].
Therefore each *year* (y) is composed by *m seasons (ls)*, *n daytipes (ld)* occur in each season in a recursive way, and *p* subsequent *dailytimebrackets (lh)* occur in each *daytipe*. The *timeslices* use allows both a reduction of the complexity of the problem and a solution of multi-year optimal planning problem.

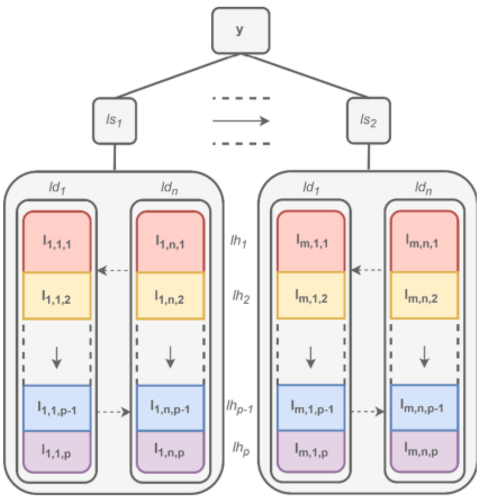

Figure 2.6: Temporal sequence of *timeslices (l)* obtained combining *seasons (ls)*, *daytypes (ld)* and *dailytimebrackets (lh)* [33].

The main consequence of this approach is that the time related parameters, such as the power load profile, or the variable renewable energy sources capacity factors, are obtained as average. In this way, it is possible to better follow the energy consumption variation, but is not suitable for other time series, such as the one related to the variable renewable energy sources.

Nevertheless, it is possible to use a different time series representation, such as the clustering one (figure 2.7). In this way, it is possible to define representative days by means of a clustering process, based on specific attributes, such as the time series of specific fuel demand and of the productivity from renewable technologies [33].

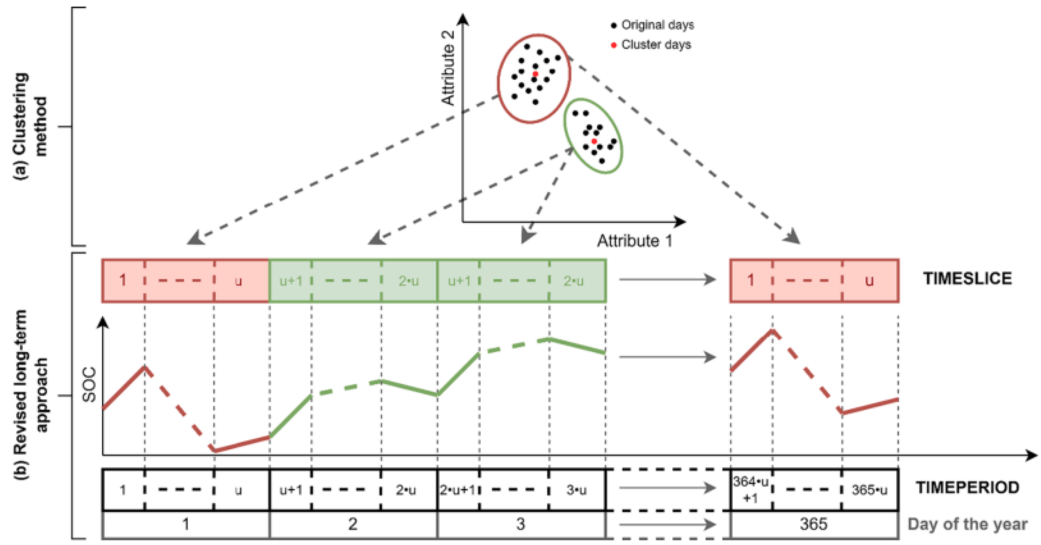

Figure 2.7: Steps of the methodology: (a) clustering method applied to the original time series to generate inputs for the long-term energy model; (b) revised long-term approach in which timeslices are decoupled from seasons and daytypes [33].

The grouping of the time series is based on a distance measure of the attributes between the different group members. There are different clustering approaches and the k-means technique is the one who has been proven its effectiveness in the energy systems applications. K-means clustering creates the clusters minimizing the squared error between the empirical mean of a cluster and all the candidates of the cluster. In this way, it is possible to preserve the total value of the original time series for each attribute.

In this case study, it is considered the clustering time series approach. The input attributes to the k-means approach are the time variable profiles related to the electricity demand, and onshore and offshore wind and photovoltaic capacity factors timeseries [34]. In particular, it is considered as reference year for the electricity demand the 2019 [35], due to the fact that the 2020 year has a lower demand profile, due to the Covid-19 shutdowns, and that the 2021 year is still facing some long-term effects determined by the lockdown [36]. In figure 2.8, solar, onshore and offshore wind capacity factors evolution along year 2019 are shown, also combined with the electricity demand.

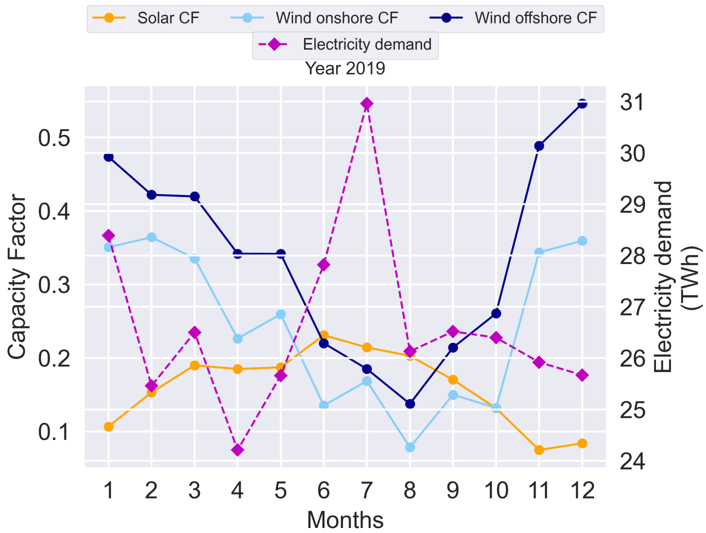

Figure 2.8: Photovoltaic, wind capacity factor, and electricity demand.

From the figure 2.8, it is possible to appreciate the three curves evolution through the 12 months of the year. In particular, it is interesting to notice that the solar capacity factor reaches its higher values during the summer season, while the wind capacity factor is higher in the winter period. Nevertheless, it is also evident that the Italian electricity demand has a sharp increase during the summer season, when the higher demand is due to the higher use of air conditioning.

2.2.3 Technical parameters

The next step is the assessment of the different technologies considering their features in both technical and economic aspects. It is important to underline that in the first step of this case study, it is considered the actual Italian electricity state.
First, the classification of the different technologies in extraction, import, export and conversion technology, in which RES technologies are considered as extraction technologies. Then, it is computed a series of other important attributes:

- Output/input flow: assessment of the energy content of each energy vector of the Reference Energy System.

- Output/input to activity ratio: ratio between the output/input of a primary commodity flow with respect to the rate of activity associated to a specific technology.

- Availability factor: maximum time a technology can run in a year.

- Capacity factor: average capacity available over one year, with respect to the total installed capacity.

- Capacity to activity unit: it is a conversion factor that considers the energy can be produced when totally using one unit of capacity in one year.

- Emission activity ratio: emission factor related to a technology per unit of activity.

- Operational life: lifetime associated to each technology.

- Residual capacity: residual lifetime associated to each technology after the first year of installation.

2.2.3.1 Output/Input flow and Output/input to activity ratio

InpActRat, *OutActRat*
In this case study, the input and output flows considered are the ones associated with the electricity flow. The data related to the energy content of the energy vectors are provided by the European Statistic, which last data are updated at 2020 [37]. Therefore, also the activity ratios are computed considering those energy parameters.

2.2.3.2 Availability factor

AvaFac
The availability factor is an important parameter because each technology cannot operate for the entire time of a year due to maintenance breaks. It expresses the average capacity available in a year as a fraction of the total installed capacity and thus takes into account planned outages. Each power plant is characterised by a specific availability, which depends on the type of power plant (traditional or renewable), the design of the power plant and its mode of operation, i.e. the operational functioning of the power plant components, but also the grid regulation [38]. The availability factors can take values between 0 and 1 as shown in table 2.1.

Table 2.1: Availability factors for the different technologies.

Technology	**Availability factor**
COAL_EL	0.90
OIL_EL	0.90
GAS_EL	0.90
NONREN_MUNWASTE_EL	0.90
NONREN_INDWASTE_EL	0.90
COAL_CHP	0.90
OIL_CHP	0.90
GAS_CHP	0.90
NONREN_MUNWASTE_CHP	0.90
NONREN_INDWASTE_CHP	0.90
WIND_PP	0.95
PV_PP	0.98
GEOTHERMAL_PP	0.90
LIQUIDBIOFUELS_EL	0.90
PRIMARYSOLIDBIOFUELS_EL	0.90
REN_MUNWASTE_EL	0.90
BIOGASES_EL	0.90
LIQUIDBIOFUELS_CHP	0.90
PRIMARYSOLIDBIOFUELS_CHP	0.90
REN_MUNWASTE_CHP	0.90
BIOGASES_CHP	0.90
HYDRO_RESERVOIR_PP	0.95
HYDRO_ROR_PP	0.95
HYDRO_PUMPED	0.95
WIND_OFFSHORE_PP	0.95
ELY	0.98
FC	0.98
BATTERY_TECH	0.95

2.2.3.3 Capacity factor

CapFac
The capacity factor expresses the average capacity available over one year compared to the total installed capacity associated to a specific technology, and it is directly related to the fuel resource. It is the ratio between the actual electricity produced and the electricity produced if the plant would be able to work at the nominal power for the same time interval.
In this case study, a major importance is given to the solar and wind capacity factors [34], considered as variable with time, in particular with a hourly resolution. The aim is to properly consider the actual renewable solar and wind sources, without neglecting their patterns. In fact, all variable renewable potentials are strictly related to the weather and thus on the weather year chosen.

Weather year 2016

It is important to underline that the 2016 year is identified as the most-typical reference year for Italy [39].

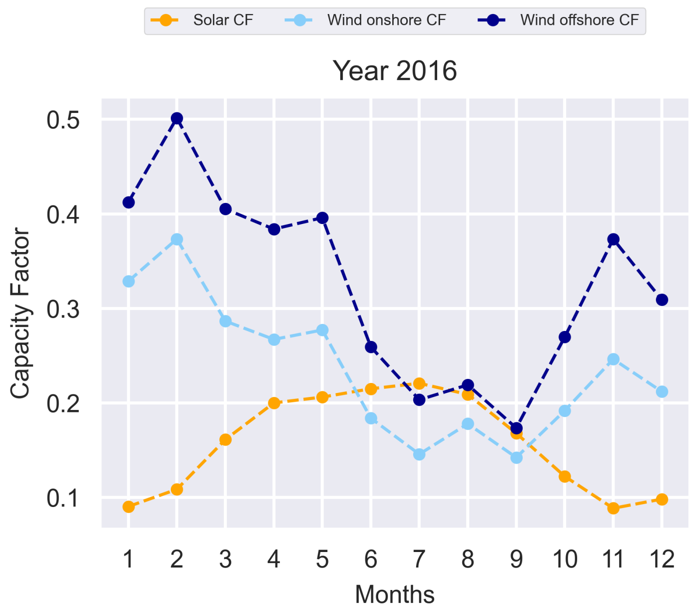

Figure 2.9: Photovoltaic and wind capacity factor of the 2016 reference year.

As it is possible to appreciate from the figure 2.9, the variation of the wind

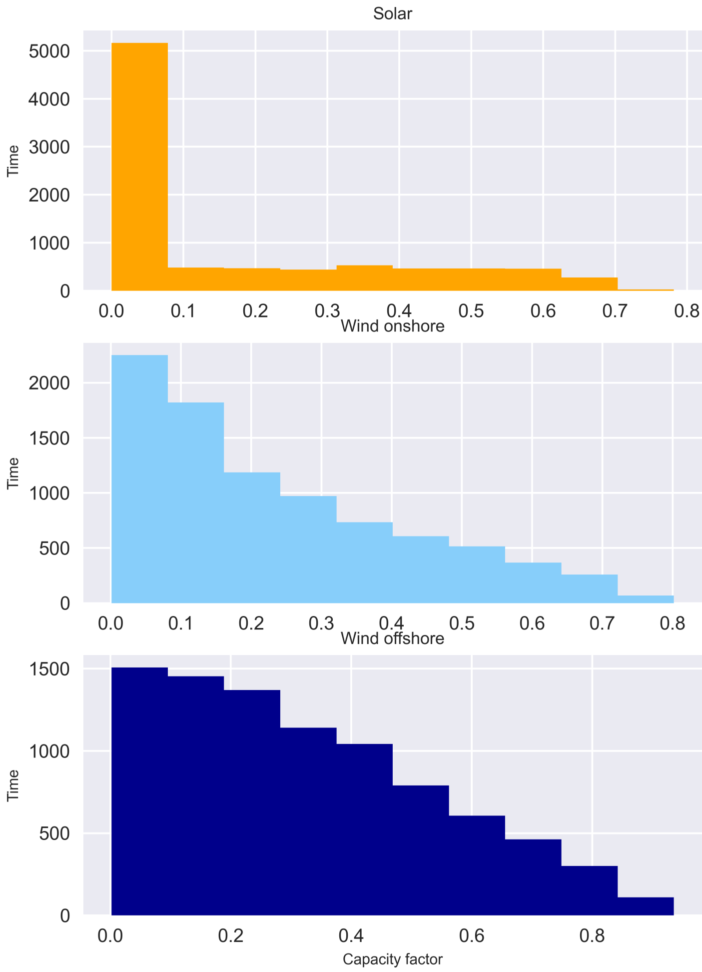

Figure 2.10: Photovoltaic, wind onshore and wind offshore capacity factor histogram distributions.

onshore and offshore, and solar capacity factors is highly different: the solar capacity factor reaches its higher values in the summer season, from June to August, facing a strong decrease during the winter; instead onshore wind capacity factor reaches its highest values during the Winter season, with a strong decrease during the summer. Then, the offshore wind is the resources reaching higher values of capacity factor. Thus, those renewable resources behave in a quite opposite way. Moreover, from the histogram plots in the figure 2.10, it is evident that for most of the time, the solar capacity factor ranges low values, below 0.1, while on the other side the onshore wind capacity factor ranges higher values, most of the time up to 0.2 and also reaching a higher value of maximum capacity factor, which is 0.8. Finally, the offshore wind capacity factor ranges higher values, also above 0.8.

Capacity factor analysis

In this case study it is considered as weather year the 2019 in order to elaborate the capacity factors of both the solar and wind source. This choice is due to the fact that the 2019 is the reference year for the electricity demand load and therefore it is not neglected the correlation between the weather and the demand. It is performed a specific analysis considering the capacity factor data from 2000 to 2019 [40], in order to exclude the 2019 as an exceptional and unusual year. Moreover it is also compared with the reference weather year 2016, as shown in the figures below.

Solar Capacity factor
Considering the solar capacity factor values, shown in the figure 2.11 and 2.12, the highest capacity factor values are reached during the summer season, from May to September. Also in this case, the year 2019 follows the mean pathways of the capacity factors of the decades before, therefore it has a comparable variation. Also compared with the year 2016, it follows the same trend, without showing any particular exception.

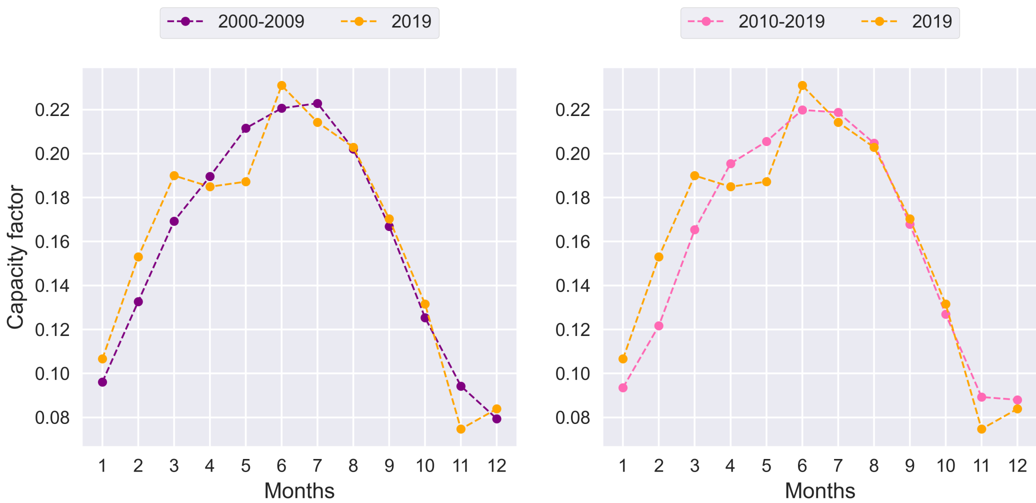

Figure 2.11: Solar capacity factor analysis.

Moreover, as shown in the histogram distribution in figure 2.13, the capacity factor values arrive up to 0.10 for most of the time and reaches also 0.70 values but only for extremely short periods. The mean solar capacity factor over the 2019 is equal to 0.161.

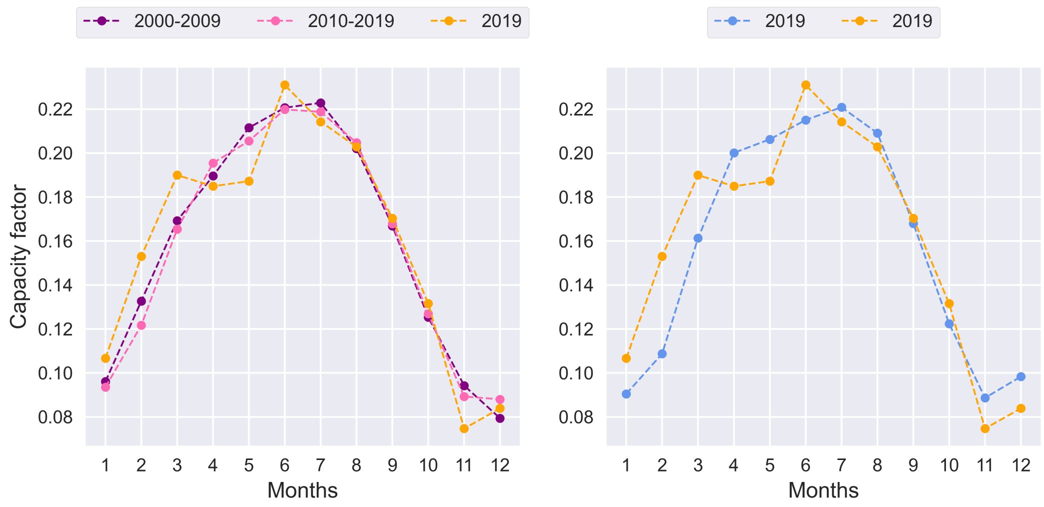

Figure 2.12: Solar capacity factor comparison.

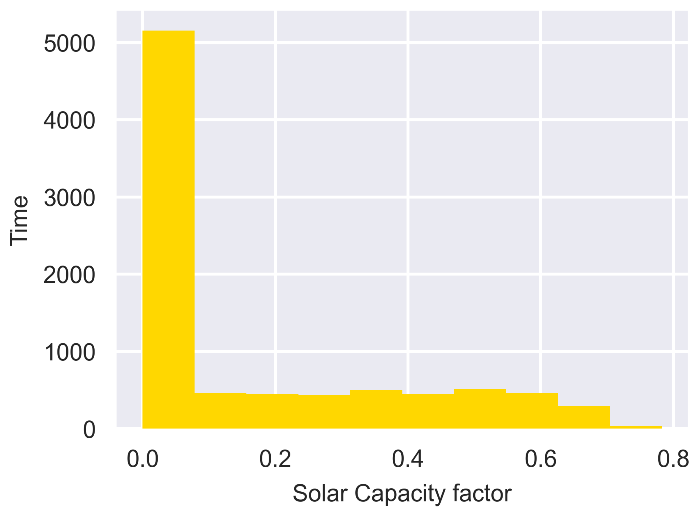

Figure 2.13: Solar resource histogram distribution.

Wind Capacity factor

As it is possible to appreciate from the figures 2.14 and 2.15, the highest capacity factor value is reached during the winter season, from December to March. In addition, the year 2019 follows the mean pathways of the capacity factors of the decades before, showing a mean suitable variation. It is necessary to highlight that the curves referred to the decades 2000-2009 and 2010-2019 show lower values of capacity factors due to the fact that they are obtained as an average, thus flattening possible capacity factors peaks or lower values. Also compared with the year 2016, it follows the same trend, except for the December month.

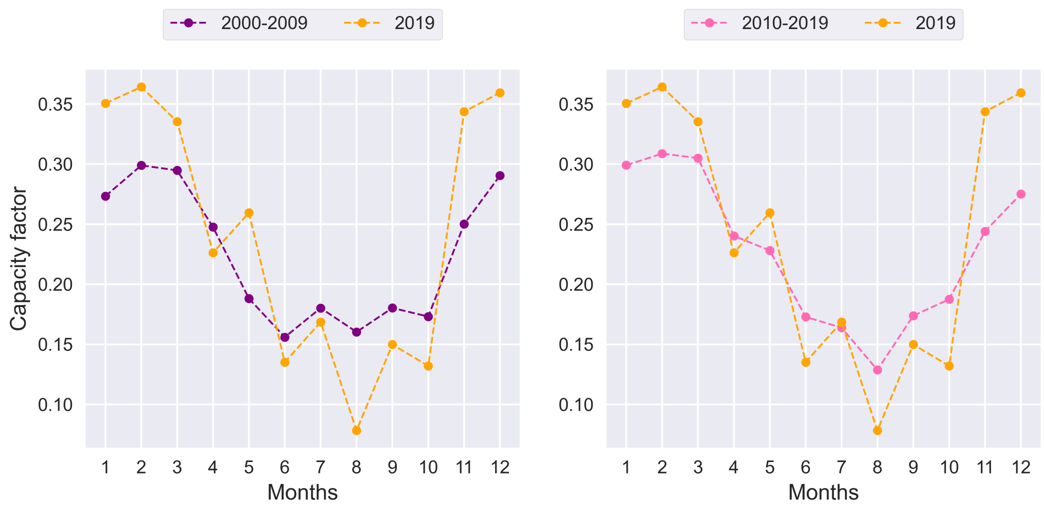

Figure 2.14: Wind onshore capacity factor analysis.

Moreover, as shown in the histogram distribution in figure 2.16, the capacity factor values arrive up to 0.20 for most of the time and reaches also 0.80 values, as the 2016 reference year. The mean onshore wind capacity factor over the 2019 is equal to 0.241.

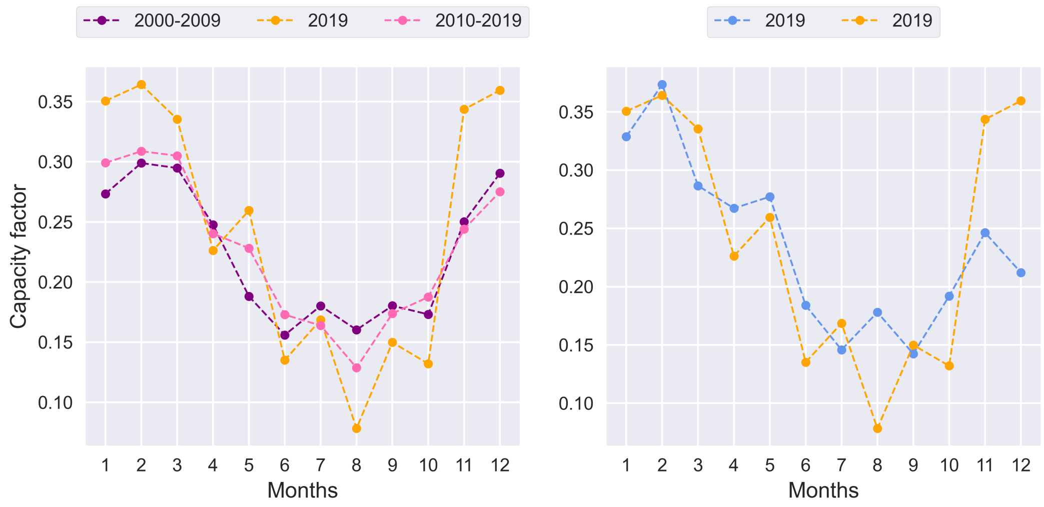

Figure 2.15: Wind onshore capacity factor comparison.

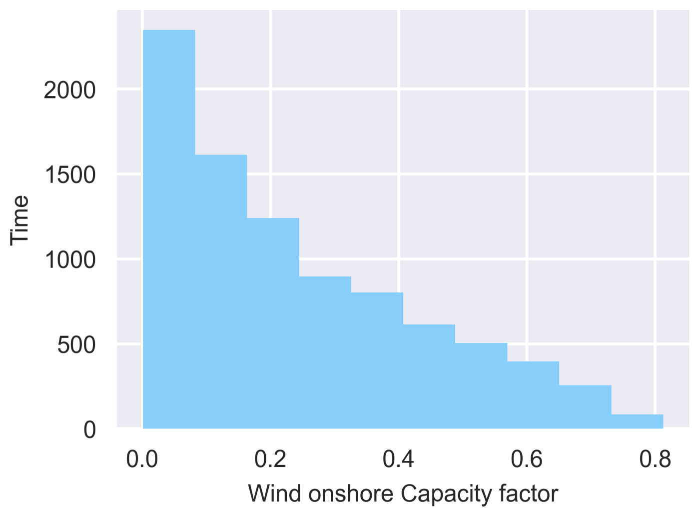

Figure 2.16: Wind resource histogram distribution.

Wind offshore capacity factor

The offshore wind source referred to the 2019 shows a coherent behaviour and trend with respect to the previous averaged decades and also considering the reference year 2016 (figure 2.17). Moreover, it is possible to appreciate from figure 2.18 that most of the offshore wind resource is available in the winter period, from December to March and the only exceptional values of capacity factor are present for the December month, as for the onshore wind resource. Also the histogram distribution is coherent with the one of the reference weather year 2016, showing for most of the time values lower than 0.4, reaching maximum values above 0.8. The mean onshore wind capacity factor over the 2019 is equal to 0.337.

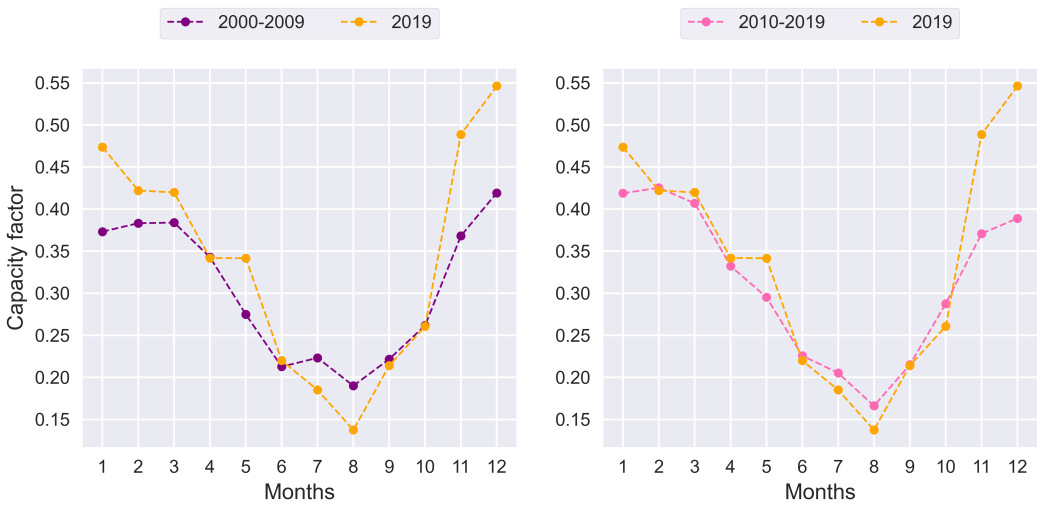

Figure 2.17: Wind offshore factor comparison.

Therefore, considering the year 2019 in order not to lose the relation between the electricity demand and the natural source allows a reasonable analysis, due to the fact that the 2019 is in agreement with the 2016 year, which is indeed the reference weather year for Italy [39].

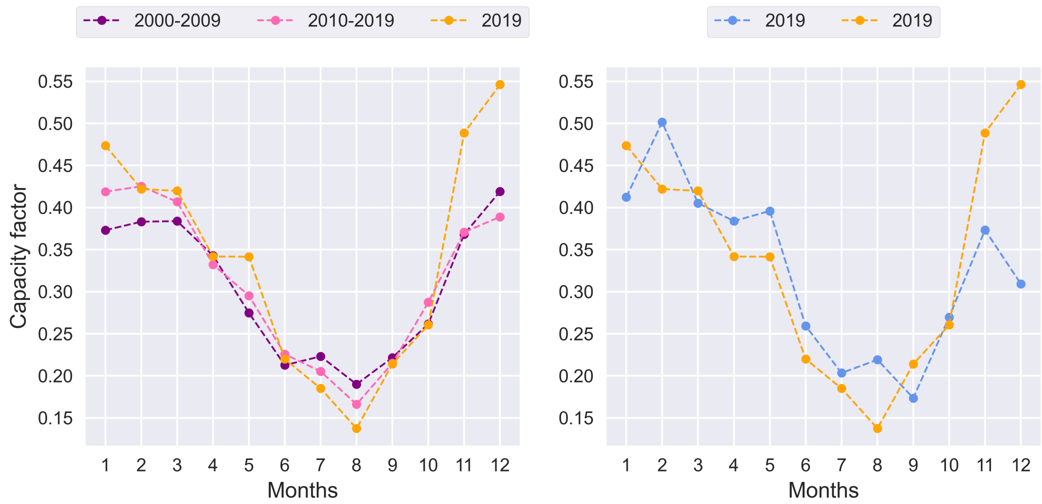

Figure 2.18: Wind offshore capacity factor analysis.

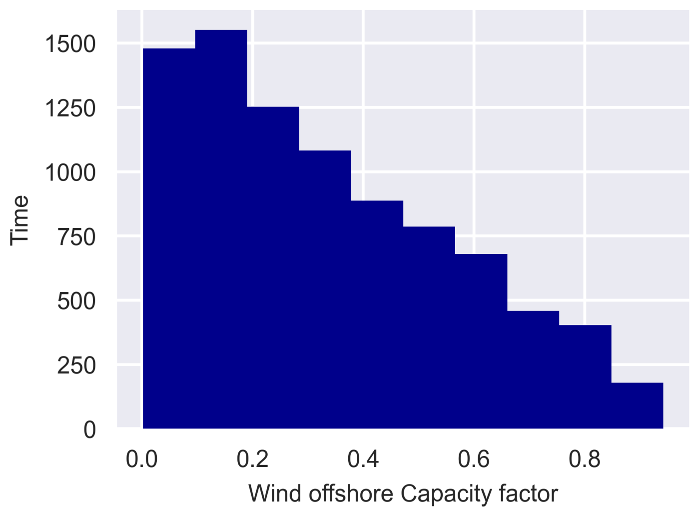

Figure 2.19: Wind offshore histogram distribution.

Fossil fuel sources capacity factor

Fossil fuel based plants, such as solid fossil fuel, oil and petroleum products, natural gas, non renewable municipal waste and non renewable industrial waste, values of capacity factor are provided by the European Commission [41]; while the biomass base power plant, such as liquid biofuels, primary solid biofuels, renewable municipal waste, biogases, capacity factor values are provided by the International Energy Agency [42].
Availability factor and capacity factor values are shown in the table.

2.2.3.4 Emission activity ratio

EmiActRat
This parameter express the emission factor related to a technology per unit of activity. In particular, it is specific for each fuel used within a power plants. Considering the fossil fuels, solid fossil fuels and oil and petroleum products have the highest emission factor, while the natural gas shows the lower one. Moreover, the emission factor related to the electricity production of non renewable waste is high [43]. Specific CO_2 emission of a fuel in relation to 1 kWh of electricity produced, is expressed in g_{CO_2}/kWh_{el}, that in this model is then converted in $kton_{CO_2}/GWh$. In addition, it is possible to also consider the emission directly connected to the primary energy content of each fuel.

In this case study, the emission activity ratio is considered with respect to the energy content of the fossil fuels, such as the solid fossil fuel (coal), oil and petroleum products and natural gas; while for the non renewable municipal and industrial waste it is considere associated to the kWh_{el}. Besides, also the import of electricity is characterized by a rate of emission, which is assumed as constant from 2021 to 2050, though it is a pessimistic assumption. Also the biomass power plants are characterized by a rate of emission, though they are contained with respect to fossil fuels.

Emission activity ratio values are shown in the table 2.2.

Table 2.2: Emission activity ratio.

Technology	**Emission rate (ktonCO2/GWh)**
COAL	0.338
OIL	0.264
GAS	0.201
ELECTRICITY IMPORT	0.226
BIOMASS PLANT	0.127
NON RENEWABLE WASTE PLANT	1.16

2.2.3.5 Capacity of one technology unit

CapOfOneTecUnit
The capacity of one technology unit is an important parameter in order to define the sizing of new capacity to be installed. In particular, the technology is installed only in batches of the specified capacity. Nevertheless, the problem turns into a Mixed Integer Linear Problem. For this case study, it is assumed as equal to 0 in order to avoid high computational time to obtain the optimal sol

2.2.3.6 Operational life

OpeLif
The operational life expresses the number of year a specific technology can last, thus its lifetime. Each technology has a specific operational life: at the end of this period it can be decommissioned or replaced by new capacity. Nevertheless, in reality it is possible to dismantle a power plant before its technical life is over. It is due to the fact that at some point, it can be more convenient to directly install a new capacity rather then go on running the plant itself.

Operational life values are shown in the table 2.3.

Table 2.3: Operational life for the different technologies.

Technology	**Lifetime**	**Technology**	**Lifetime**
COAL_EL	30	LIQUIDBIOFUELS_CHP	25
OIL_EL	40	PRIMARYSOLIDBIOFUELS_CHP	25
GAS_EL	30	REN_MUNWASTE_CHP	25
NONREN_MUNWASTE_EL	25	BIOGASES_CHP	25
NONREN_INDWASTE_EL	25	WIND_PP	25
COAL_CHP	30	PV_PP	25
OIL_CHP	40	HYDRO_RESERVOIR_PP	55
GAS_CHP	30	HYDRO_ROR_PP	55
NONREN_MUNWASTE_CHP	25	HYDRO_PUMPED	55
NONREN_INDWASTE_CHP	25	WIND_OFFSHORE_PP	20
GEOTHERMAL_PP	30	ELY & FC system	20
LIQUIDBIOFUELS_EL	25	ELY & FC stack	10
PRIMARYSOLIDBIOFUELS_EL	25	BATTERY_TECH	10
BIOGASES_EL	25		

2.2.3.7 Residual capacity

ResCap
The residual capacity considers the amount of power installed for each technology and its decrease in time. In fact, considering that each power plant has a limited lifetime, it is possible to predict the end of the operation. This limit is due to different reasons: phase out targets, economic aspects and also technical aspects. Thus, at some point it can be more convenient to shut down a plant before its operational life is over and install a new one to replace the capacity. In this case study, the residual capacity of each technology from 2020 to 2050 is elaborated considering the power plant installation since 2000 [9].

Residual capacity values are shown in the figure 2.20.

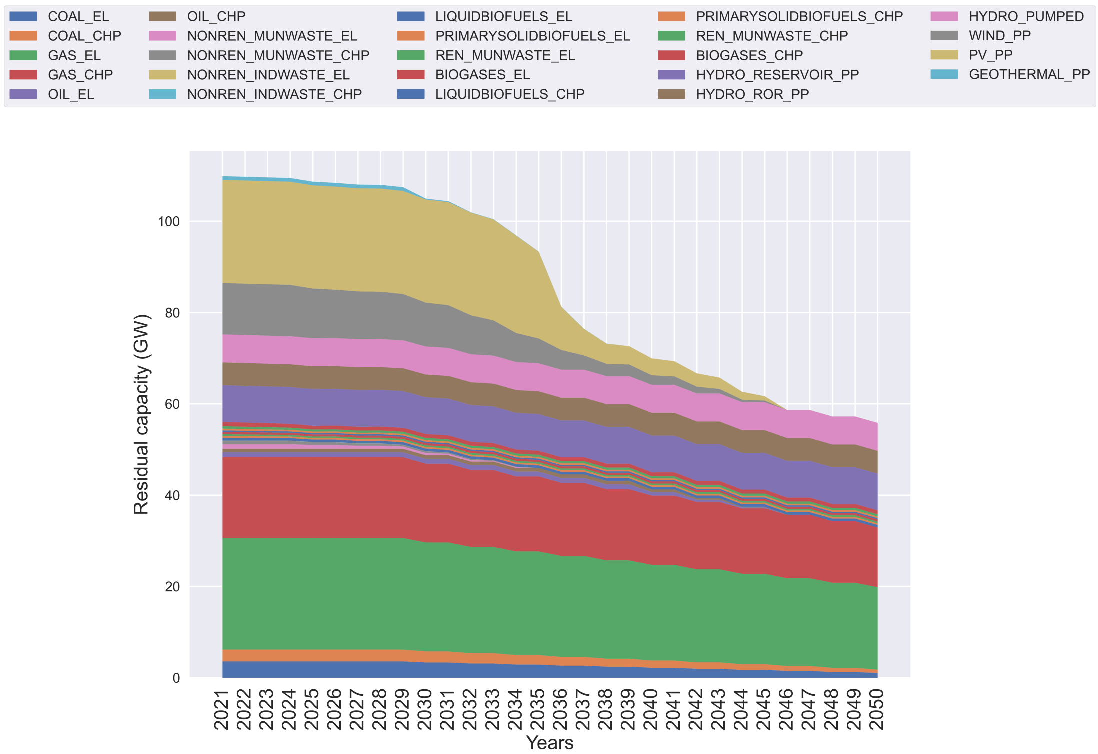

Figure 2.20: Residual capacity.

2.2.3.8 Dispatchable generation

DGTagTechFuel, *DGTimeSliceLowLimRat*
The dispatchable generation parameters are necessary in order to introduce a

specific limitation. In fact, it is necessary to set at least a minimum share of 20% electricity production supplyed by dispatchable technologies, following the minimum share of instantaneous conventional generation set by the European Transmission System Operators [44].

2.2.3.9 Technology and storage

TecToSto, *TecFroSto*
Technology to storage and technology from storage are two parameters necessary to link the technology to the storage. In particular, the first one is necessary to specify a technology to the storage facility it charges and it is a binary parameter, while the latter connects the storage facility to the technology it feeds and it is expressed considering the discharge efficiency of the storage component. Therefore *TecFroSto* is specified for the battery and of the fuel cell which inject the electricity again into the grid.

2.2.3.10 Battery storage parameters

EnerPowRatioMin, *EnerPowRatioMax*
It is necessary to underline that the sizing of the rated power and the rated energy of storage systems are performed separately. Therefore the analysis is performed assuming different costs for the power-components, which are modelled as *technologies* (BATTERY_TECH, ELY, FC) and for the energy-components, which are modelled as *storages* (BATTERY_STORAGE, HY_TANK). Nevertheless, this approach is well suited for the hydrogen P2P solution, while it is not appropriate for the batteries. In fact, electrochemical storage technologies such as Li-ion batteries, are characterized by specific ranges of values of energy-to-power ratios. Therefore, in order to perform a correct sizing of the battery storage system, it is set e minimum energy-to-power-ratio equal to 0.5 (*EnerPowRatioMin*) and a maximum energy-to-power-ratio equal to 2 (*EnerPowRatioMax*) [45].

2.2.3.11 Specified Annual demand, Specified Demand profile

SpeAnnDem, *SpeDemPro*
By means of those two parameters, the demand side is defined and specified for the whole model period. Indeed, it is assumed an electricity demand evolution from the Italian National Trends [46] by 2040 which relies on a modelling tool, also taking into consideration the PNIEC plan and the National Trend results developed by ENTSO-E and ENTSOG for the Ten Year Network Development Plan (TYNDP) 2020. Therefore the electricity demand projection is obtained considering the electricity market and also guaranteeing the minimum electricity needs in order to ensure the minimum dispatchable constraints and all the different energy system security. Then, for this case study, it is assumed an electricity demand evolution from 2040 to 2050 as the rate of increase from 2030 to 2040.

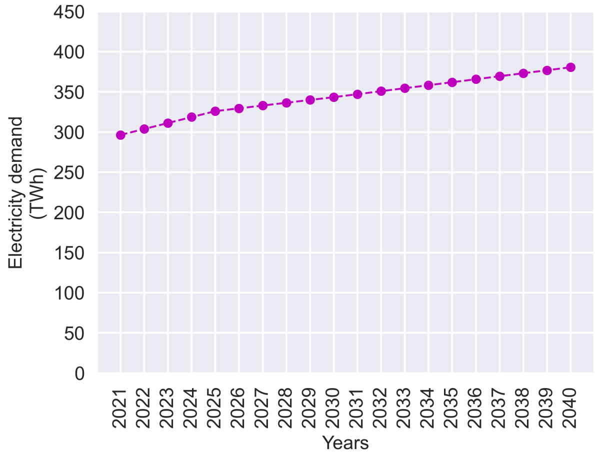

Figure 2.21: Electricity demand projection [46].

2.2.4 Economic parameters

In order to develop an energy system model, it is necessary to consider besides the technical parameters also the costs. In particular, it is necessary to estimate the actual and future capital and operational costs, by means of cost projections in order to better assess the possible evolution and role of each technology in the future.

2.2.4.1 Capital cost

Capital expenditures (CapEx), also called overnight costs, are the initial investment done in order to build a power plant, without considering the financial costs, thus the interest rates, or the structure of financing, thus cost of equity and cost of debt. In general, it includes property, plant and equipment (PPE) assets. It is expressed as €/kW, so with respect to the installed capacity. Moreover, renewable clean power plants are characterized by higher capital costs compared with fossil fuel based plants, which are mature technologies. Nevertheless, those new developing renewable technologies are still in development, therefore they will face a strong cost reduction.

Solar capex

Solar photovoltaic is the cheapest technology for electricity production on many countries and market segments [47]. In the last decades, PV module prices have decreased more than 90% and system prices by 80%, and will continue to decrease following a steady and high learning rate (LR) of 39.8% for PV modules between the period 2006-2018. PV is the energy technology which faced the fasted and steepest cost decrease, thanks to the China in the manufacturing side and US as investor support. Moreover, the higher demand due to European policies has been a triggering factor[41]. The solar photovoltaic capital cost is expected to drop drown from 560 €/kW in 2020 to 290 €/kW in 2050 considering utility-scale photovoltaic plants [48].

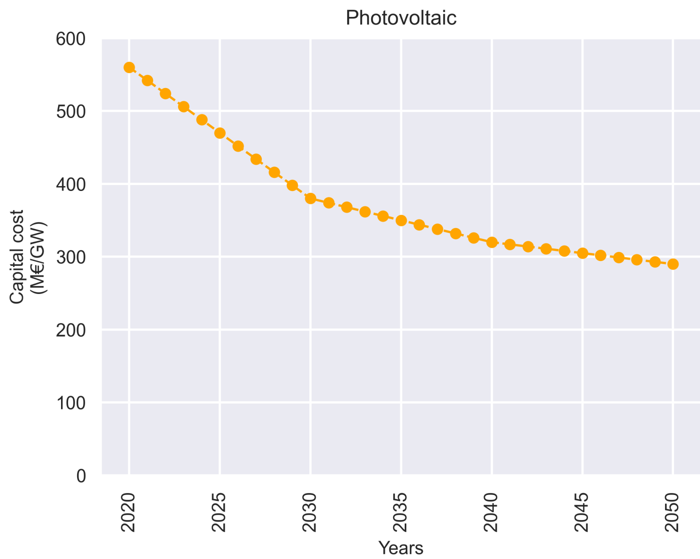

Figure 2.22: Solar photovoltaic capex.

Wind capex

Wind is one of the fastest growing sources in order to generate electricity [49]. In particular, it has been registered a strong installed capacity increase due to the strong reduction of wind energy cost, comparable to the conventional electricity generation technologies. Lower costs are due to important technological improvements both in term of performances and operational lifetime.

Onshore wind energy has face a strong costs decline up to 2002-2003, when an increase of commodities prices of raw materials stopped this pathway. Nevertheless, the global financial crisis of 2008-2009 caused a decrease of the turbine capital costs: both energy and steel prices dropped down. The average onshore wind turbines price dropped down of 9-18%[41]. The onshore wind cost is expected to drop down from 1120 €/kW in 2020 to 960 €/kW in 2050 [48].

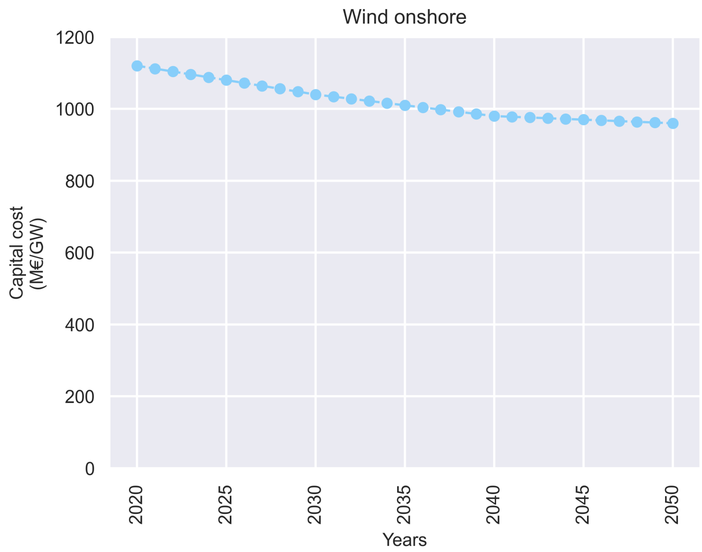

Figure 2.23: Wind onshore capex.

Offshore wind energy total installation costs are 2-3 times the equivalent costs of onshore wind plants, but are able to produce a higher energy yield because of a more constant wind available offshore. This technology has faced a cost increase due to physical characteristics such as the higher distance from the shore and the higher water depth. After facing a peak in 2012, the offshore wind technology has faced a strong capital expenditure decrease of 8-31% [49]. The offshore wind cost is expected to decrease from 2120 €/kW in 2020 to 1680 €/kW in 2050 [48].

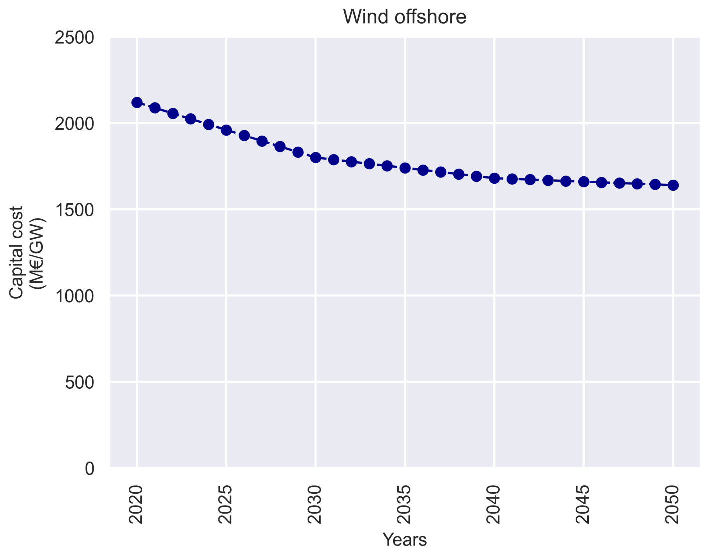

Figure 2.24: Wind offshore capex.

Capex and Capacity factor
There is a strict dependence between the capex and the capacity factor. Indeed, it is necessary to underline that the values of capacity factor used for this study, are referred to the natural source available and especially exploited by means of the actual technologies available. Therefore, it is conservative to assume that also in the future both the capacity factor and the costs associated to a technology will follow the nowadays perspective. In particular, by means of the future technological development, it is be possible to achieve higher capacity factor values associated to the renewable technologies, such as onshore and offshore wind plants, and photovoltaic plants. Nevertheless, on the other side, those innovative technologies are expected to have higher capital costs. In this case study, renewable sources are assumed as in the actual level of technological development and thus also the capacity factor values associated, underestimating the real future gain it is possible to reach in the future [50].

Battery capex

Battery storage cost has decreased rapidly in the past decades, stimulating a higher interest for this kind of technology and also in its potential role with RES power plants. As explained before, the most suitable battery technology for utility-scale energy storage are Li-ion batteries, thanks to their features. Their cost is split into power and energy cost, expressed respectively in €/kW and €/kWh [51].

Li-ion batteries capex cost has face a strong decrease and considering the future projections it will drop from 228.12 €/kW in 2020 to 57.03 €/kW in 2050. Indeed, this cost reduction will be determine thanks to manufacturing and efficiency improvements combined with economies of scale.

Figures 2.25 and 2.26 show the Li-ion capex power component and energy component evolution.

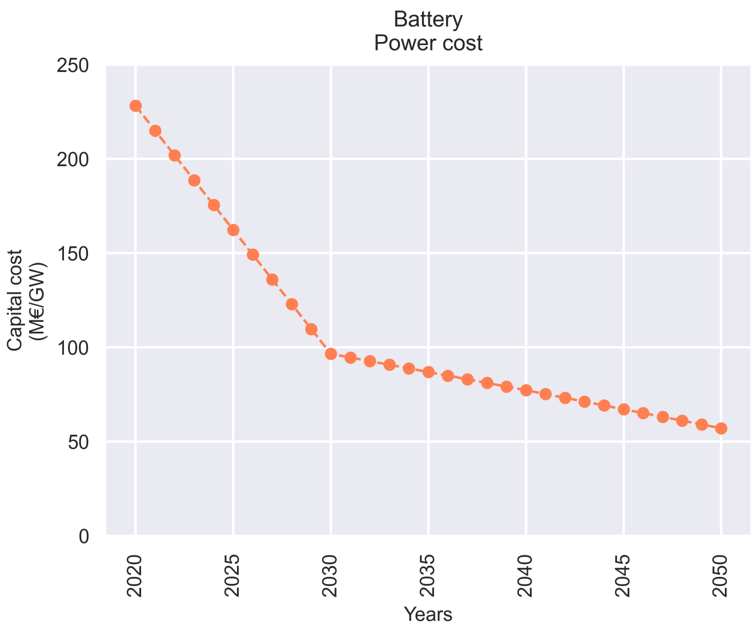

Figure 2.25: Li-ion battery power capex [51].

Electrolyzer and fuel cell capex

Contrary to the other technologies, electrolysis cost reductions will be more limited due to high capital costs and uncertainty fro their commercialization and development. The capital cost projection shows a drop from 1188 €/kW in 2020 to 314 €/kW by 2050 [52]. Besides, considering fuel cells technology will face a capex decreasing evolution from 1520 €/kW in 2020 to 650 €/kW by 2040 [53]. For this

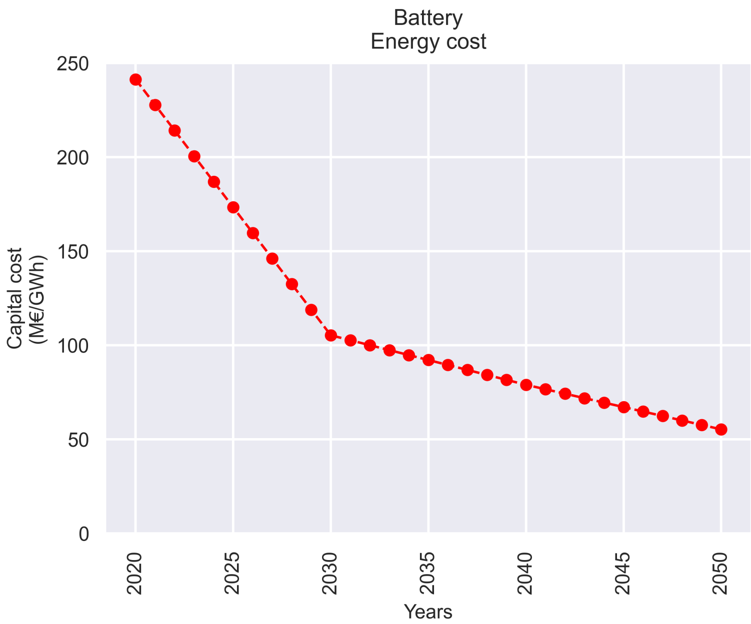

Figure 2.26: Li-ion battery power capex [51].

case study, which covers the period from 2021 to 2050, it is assumed a cost drop from 2040 to 2050 equal to the one from 2030 to 2040. In particular, for both electrolyzer and fuel cell technologies it is assumed a stack replacement every 10 years, which cost is computed as a percentage of the capex, respectively equal to 40% and 50% [54]. Concerning the hydrogen tank, it is assumed no cost evolution over the time period considered, due to the high maturity of steel pressure vessel technology [54].

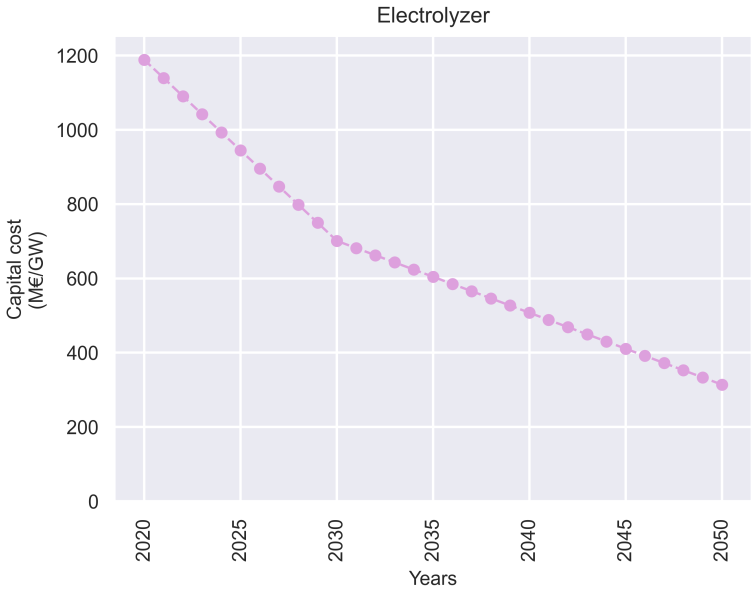

Figure 2.27: Electrolyzer capex [52].

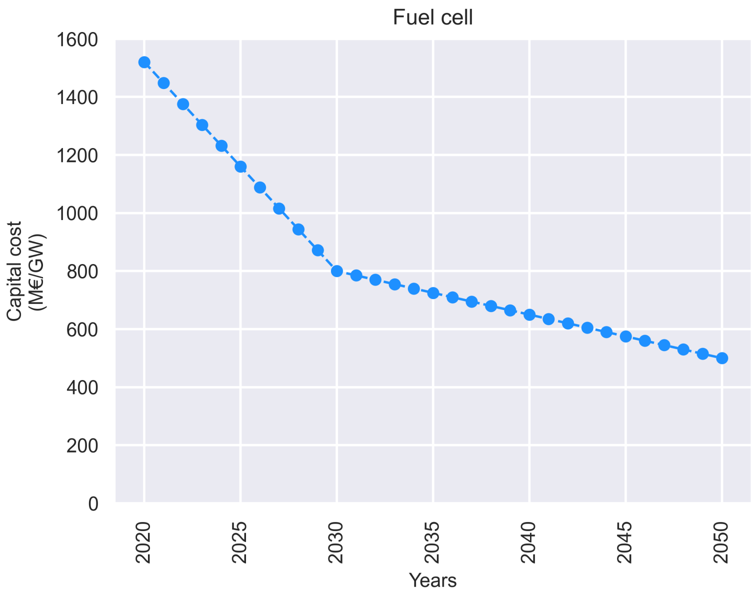

Figure 2.28: Fuel cell capex [53].

2.2.4.2 Operational and maintenance cost

Operating expense (OpEx) are related to the normal running of a business. Opex expenditures are composed by variable and fixed costs, which are respectively the cost of a technology per unit of activity, thus in €/kWh, and the yearly fixed operation and maintenance cost per unit of capacity, thus in €/kW/year. Variable costs are due to the consumption of basic commodities including labor, commissions and raw material costs, and depends of the output produced, while fixed costs are constant costs independent from the rate of production of the plant and can include rent costs, insurances, salaries.

Chapter 3

Potential assessment

The potential assessment is an important step to identify the actual possible feasible renewable sources and their possible exploitation. In particular, this kind of analysis is necessary in order to contribute to the energy and environmental targets of the last years. Indeed, different studies are performed in order to estimate the actual available potential, which has to be computed in a cost-efficient and socially acceptable way [55]. Moreover, the last year significant attention to this area, has led to various methodological improvements and more solid potential estimation. These enhancements are referred to finer atmospheric modelling and data availability, land mapping and technical-economic features. There has been also a focus on non-technical constraints for renewable resources, such as the social acceptance. Thus, the best and most reliable approach is not identified yet, but different methodologies are available from the literature.

In particular, in the potential assessment field of renewable energies, the potential is distinguished in five different categories [56], which are:

- Theoretical potential: it is the physically available energy considering a specific region and time.
- Geographical potential: it is the available area to produce energy, also considering possible constraints such as natural protected areas or land uses limitations.
- Technical potential: it is the amount of capacity can be installed considering technical constraints in a specific region and time.
- Economic potential: it is the technical potential which can be realized also considering the economic aspects.
- Feasible potential: it is the feasible economic potential, considering also other factors such as social aspects, market, since the whole economic potential

cannot be totally exploited in reality.

For this study, it is performed a potential assessment of both onshore wind and solar sources considering both theoretical, geographical and technical limitations. The method which is used relys on the Geographical Information System (GIS), which allows the use of geospatial information by means of raster layers and vector map. In this way, it is possible to estimate the technical potential of both onshore wind and solar sources. Then, the obtained results are updated considering other further studies methodologies in order to obtain more feasible results.

3.0.1 Literature: Onshore wind potential assessment

Various reviews regarding the onshore wind energy estimation are available. These consider bibliometric analyses of general trends in the potential assessment field [57], or of specific factors influencing wind energy projects [58]. Whereas, other studies consider the wind turbines history [59] and developments of wind diffusion at global level in the last decades [60]. Other studies consider the wind power generation forecasting or meteorological aspects, as wind speeds [61]. There are also studies which consider the connection between onshore wind and markets [62], environmental impacts [63], or precise evaluation of wind turbines in specific locations [64], such as urban areas [65]. There are also onshore wind potential assessment analysis focusing on specific aspects, such as wind turbine integration in the electricity grid studies [66], or in energy system planning models [67]. Other analysis just consider wind potential assessment focusing on the geographical potential [68]. Finally, there are also reviews which focus mainly on technical aspects, in a wider context of renewable resources [69]. Therefore, there is no a unique approach in order to better estimate onshore wind potential, both in geographical, technical and economic way.

3.0.2 Onshore wind technical potential assessment

The potential assessment of onshore wind sources performed in this study, relies on on the use of Geographical Information Systems (GIS), which is a useful tool to manipulate and analyse spatial and geographical data [70]. The first step is the estimation of the theoretical potential, which is the higher limit by means of Global Wind Atlas (GWA). Subsequently, it is computed the technical potential adding the different constraints. Those criteria are applied as exclusion criteria, also with buffer distances [71] or combined into indicators [72]. In this simplified assessment, constraints are used just as areas to be excluded.

3.0.2.1 Criteria description

Exclusion criteria can be divided in different categories, such as physical or technical constraints, built environmental exclusion criteria and finally constraints related to legislation, environmental limitation for flora and fauna safeguard. All these parameters are available in *shape file format* or *vector map*, which can be easily manipulated using QGIS tool.

Wind speed
The first constrain considered is the average wind speed available at 150 m altitude, which is a typical wind turbine hub height [73]. Moreover, wind speed values are considered referring to the IEC wind turbine classes (IEC 61400-1) [74], as shown in the table. Indeed, wind turbines produce electricity above a minimum wind speed (*cut-in wind speed*), and the electricity production is interrupted once is reached the maximum wind speed the turbine is able to withstand (*cut-off wind speed.* Thus, only the areas with a wind speed in the range 6 - 10 m/s at 150 m are assumed as theoretical exploitable areas.

Terrain slope
The terrain slope is another constraint due the fact that wind plant and adjacent area should not be too steep in order to easily allow installation and maintenance access to the wind turbines. Thus, it is considered as maximum acceptable terrain slope a value equal to 30% [75].

Elevation
As for the terrain slope limitation, wind turbines should not be deployed on mountains because of high installation issues and costs, and possible breakdown risk. Therefore, it is set a maximum acceptable elevation value equal to 1500 m, thus mountain chains are excluded as not exploitable areas [76].

Natura 2000 Network

The Natura 2000 is a network of nature safeguard areas in the European Union territory. It is composed by Special Areas of Conservation, designated under the Habitats Directive 92/43/CEE, and Special Protection Areas with the Birds Directive 2009/147/CE. Besides, both terrestrial and marine protected areas are included (figure 3.1).

Figure 3.1: ReteNatura2000.

Important Bird Areas

Important Bird Areas (IBAs) are key-role zone in order to safeguard birds and biodiversity, identified by Bird-Life International. It is a project which aims to establish standard criteria for the Special Protection Zones designation (figure 3.2).

Figure 3.2: IBA map.

Water bodies

Water bodies are included in the environmental constraints, in order to ensure a specific distance from lakes and rivers (figure 3.3). Indeed, it is necessary a minimum distance because the installation of wind turbines could be polluting, such as components transportation and foundation constructions. Besides, lakes and rivers are the typical habitat of several animal species, thus wind turbines could represent an issue. For the Italian case study, it is assumed a buffer equal to 200 m [77], though in the literature this value highly varies from 50 m [78]to 7 km [79].

Figure 3.3: SpecchiAcqua.

High voltage transmission network

In order to ensure the wind turbines plant electricity cabling and reduce both transmission losses and costs, it is necessary to set a distance interval. Nevertheless, it is also necessary to set a minimum distance from the power lines for safety reasons may be compromised by turbine failures [80]. The minimum distance is set to 200 m, while the upper limit is set to 10 km, though in literature strongly varies, thus depending on the specific study area. The Italian high voltage transmission network is shown in figure 3.4.

Figure 3.4: High voltage transmission map.

Railways, roads and highways

The minimum wind turbines distance from roads in Italy is set to 200 m from highways and roads [81]. This type of constraint is necessary in order to ensure safety conditions. Indeed, it is necessary to guarantee a safe minimum distance from possible wind turbine partial or total failure. Moreover, it is also necessary to limit this distance between wind turbines possible location and the road network also to minimise construction and maintenance costs [82]. The Italian road and railways maps are shown in figures 3.5 and 3.6.

Figure 3.5: Roads map.

Figure 3.6: Railways map.

Airports

A suitable distance from airports is necessary in order to minimize radar interference and also to permit both the take-off and the landing in safe conditions, without causing any distractions to the pilot's vision. In the literature, the minimum distance value assumes different values, from 500 m [83] to 7 km [84]. In this case study, it is assumed a value equal to 3 km [85]. The Italian airport map is shown in figure 3.7.

Figure 3.7: Airport map.

Urban Areas

The distance from urban areas is another limit due to several reasons, such as wind turbine failure or wind turbines noise. Thus, wind plants can be installed at a specific safeguard distance from urban areas and dwellings in general. In Italy, the minimum distance between a building and a wind turbine is equal to 200 m [86].

Once it is computed the actual available area to install wind power plants, it is considered the specific wind power plants power as equal to 7 MW/km2. The area is equal to 208380.23 km2 and thus the technical potential is equal to 1458.7 GW.

3.0.3 Literature: Photovoltaic potential assessment

As for the onshore wind potential assessment, also for the photovoltaic different estimation methodology are available in literature. Different indicators affect the estimation of the solar energy potential and exert a significant impact on the solar energy market development, such as solar energy source, land cover, technological development, economics of photovoltaic products and the government policies [87]. The major factor in the suitable area selection is the land cover [88], while the technological development influences the solar power transition efficiency [89], which has an influence over the economic feasibility of solar power generation. Besides, also governmental policies play a crucial role in the solar PV generation operation [90]. Therefore, in order to determine the real and actual photovoltaic potential assessment, it is necessary a comprehensive analysis based on both the solar energy source and also techno-economic factors [91].
There has been a considerable effort in evaluating the global ans regional solar potential, considering both ground and building rooftops. Nevertheless, different studies have estimated the direct solar source only, without considering any technical and economic aspect. There are studies which evaluate the potential for solar energy based on the Diffuse Horizontal Irradiance (GHI) and on the Direct Normal Irradiance (DNI) [88]. Other studies successfully performed the identification of suitable areas for large-scale PV plants but neglected the tecno-economic factors [92]. Only recently, new studies also focused on the technological and economic feasibility combining these factor with the solar energy potential analysis. However, there are also comprehensive analysis to assess the geographical, technical and economic potential [93][94].

3.0.4 Photovoltaic technical potential assessment

As for onshore wind potential assessment, also for the photovoltaic GIS-based method is used starting from the theoretical potential, which is the higher exploitable limit by means of Solar Global Atlas (SGA). Successively, the technical potential is estimated applying the different constraints. Also in this case, those limitation are implemented as areas to be excluded.

3.0.4.1 Criteria description

The exclusion criteria applied for the photovoltaic estimation are the same, thus technical, environmental and governmental constraints. They are available in *shapefile formart* or *vector map*, manipulated using QGIS tool.

Global tilted irradiation

The first technical constraint applied it the solar energy source, which is the Global Horizontal Irradiation (GHI), nevertheless for this case study it is considered the Global Tilted Irradiation (GTI) which is average annual, monthly or daily sum of global tilted irradiation for PV modules fix-mounted at optimum angle. Besides the minimum acceptable value is set at 1200 kWh/m2 which is the inverter activation value [95].

Natura 2000 Network, Important Bird Areas, Water bodies

As for the onshore wind potential assessment, these environmental factors are considered and excluded because of the environmental safeguard and respect.

Terrain slope

The terrain slope is another necessary parameter because steep land would make construction difficult. Besides, various slope thresholds can be found in literature, rangin values from 3% [96] to 5% [97], also reaching 20% [98]. It is assumed a slope value limit equal to 20%, as in another Italian case study.

Elevation

Photovoltaic power plants should not be built at high elevation values, due to both higher economic cost but also to difficulties in construction. Besides, the shading effect could be amplified in high elevation areas. A threshold limit elevation value is at 1500 m, thus mountain chains are excluded as not exploitable areas [98].

HV transmission network, Railways and rods, Airport

For these factors, the same value are assumed as for the onshore wind potential assessment. In particular, for the airport limitation it is not possible to install any photovoltaic plants in order to guarantee flight security and thus no interference with dazzle phenomena which could cause difficulties to both pilot's vision and to the air traffic control tower [99].

Urban Areas

Urban areas are excluded with the same criteria of onshore wind potential, because only utility-scale PV plants are considered in this potential assessment. Indeed, building PV plants near urban areas could generate a negative environmental impact on both the population and urban growth [99].

The actual available area to install utility-scale photovoltaic power plants is equal to 84854.7 km2 and considering a specific PV power density equal to 82 MW/km2, the technical potential is equal to 6958.1 GW.

In the table 3.1 the different constraints assumed are summarized.

Table 3.1: Constraints for technical potential assessment.

Parameter	**Value**
Natura 2000 Network	-
Important Bird Areas	-
Water bodies	200 m
Elevation	<1500 m
High voltage transmission network	>200 m and <10 km
Railways, roads and highways	>200 m
Airports	>3 km
Urban Areas	>200 m
Terrain slope onshore wind	<30%
Terrain slope PV	<20%

3.0.5 Demographic and political factors

As explained before, there are different key factors influencing the renewable potential assessment. Indeed, the two values estimated at this point consider only the main theoretical and technical constraints, also coupled with the environmental and governmental limitations. Nevertheless, social factors influence the planning decisions [100]. Besides, there are also studies in Great Britain which suggest a higher support for the renewable development decreases as both income and age increase [101], and people highly qualified are less likely to sustain projects [102].

However, those parameters are not considered in the geospatial analysis of the renewable potential. Therefore, in order to estimate more feasible values for both onshore wind and photovoltaic potential assessment it is considered an advanced Geospatial Information Software coupled with Multi-Criteria Decision Analysis (GIS-MCDA) approach applied for UK case study [103]. Indeed, as shown in the figure 3.8, environmental, technical and social factors are the input parameters. Each geograpical area is scored against those input factors and not suitable areas are excluded. Then, remaining sites are scored to estimate their suitability. Different techniques are used, but the Weighted Sum Method (WSM) is the most common one and it is used to combine the different layers into a single score, following this rule:

$$A_i^{WSM} = \sum_{j=1}^{n} w_j a_{ij} \tag{3.1}$$

where w is the weighting parameter, a is the parameter value and i is the model attribute layer.

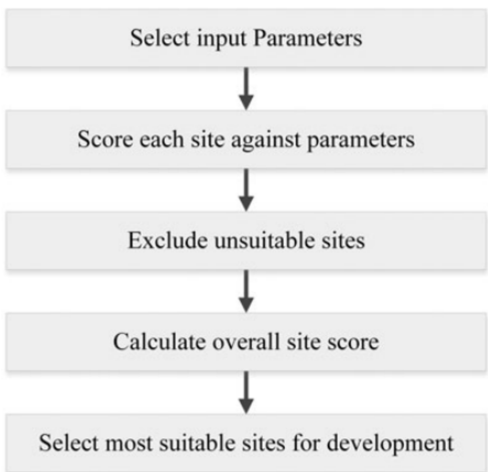

Figure 3.8: Typical structure of GIS-MCDA methodologies [103].

WSM method is often applied without any insight of the meaning of two critical parameters: the assigned weights assigned to each attribute layers and the layers combination procedure [104]. Therefore, in the advanced GIS-MCDA method considered, it is applied a multi-level approach whereby the different parameters are grouped into commensurate groups, reducing the subjectivity introduced with the parameter weighting WSM approach. Then, it is also considered the statistical analysis which considers also both social and political aspects, such as people qualification level, mean age and political orientation, which for the UK study are Labour Share and Liberal Democrat.
Therefore, from this study it is shown that starting from 200 GW of onshore wind techno-economic potential in UK, applying *soft* and *extreme* criteria, the actual feasible potential is respectively equal to 13 GW and 4 GW.

For this Italian study, due to lack in both social and political statistical parameters, it is assumed a proportion between UK and Italian potential assessment results, also assuming that those two factors effect onshore wind a photovoltaic plants installation in the same way. In the table 3.2 the main results obtained are summarized .

Table 3.2: Onshore wind and photovoltaic potentials for *soft* and *extreme* case.

GW	**Onshore wind**	**PV**
soft	86.2	411.2
extreme	26.5	126.5

3.0.6 Offshore wind potential assessment

Nowadays, no offshore wind power plants is installed in Italy contributing to the electricity production. Nevertheless, several efforts are performed in order to exploit and develop also this technology, and also the Italian Government simplified the bureaucratic procedures and announced its inclination to further encourage offshore wind expansion.
In the figure 3.9 the wind speed at 150 m is shown.

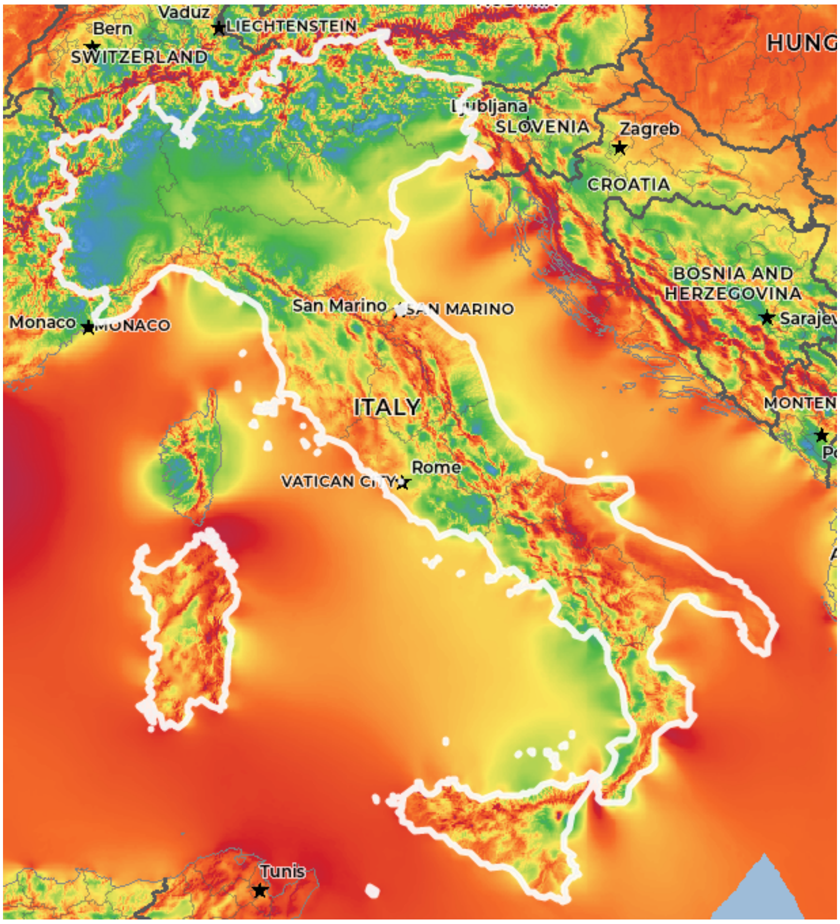

Figure 3.9: Offshore wind speed at 150 m [15].

Besides, various offshore wind projects are expected to be developed:

- GreenIT, composed by Plenitude (Eni Group) and CDP Equity for the installation of a plant in Sicily and in Sothwest Sardinia
- Falck Renewables and Bleu Float Energy for two projects in Southern Sardinia, a project in Northeastern Sardinia ans one in Puglia

- Seawind for two projects in Southwest Sardinia
- Energy Wind 2020 for a project off Rimini coast in the northern Adriatic Sea
- Renexia for a project off Egadi islands and one off the Sardinia coast
- Agnes for a project off Ravenna coast in the northern Adriatic Sea

Offshore wind potential accounts for 5.5 GW up to 2030, estimated by Italian wind energy association ANEV. Besides, thanks to the new national electricity transmission grid improvement by TERNA, the future and feasible capacity can be installed accounts for 95 GW [105].
For this case study, it is assumed a maximum potential equal to 5.5 GW until 2030, and then equal to 95 GW up to 2050.

Chapter 4

Scenario definition

The energy model defined is implemented in order to study different scenarios. In particular, elaborated varying the storage technology to analyse the storage facilities role coupled with the RES systems penetrations. Beside, in each scenario the electricity demand evolution is the same in order to better allow a comparison between the different configurations.

1. Only Battery (OB):

   - Carbon-phase out by 2025 of the different fossil fuel technologies, with exception of the natural gas which is could be still considered in the future energy mix.
   - PNIEC trends considering the biomass power plants, hydropower power plants and geothermal power plants.
   - Onshore and offshore wind potentials limitation.
   - Solar potential limitation.
   - Battery Li-ion system as new storage technology.

2. Only Hydrogen (OH):

   - Carbon-phase out by 2025 of the different fossil fuel technologies, with exception of the natural gas which is could be still considered in the future energy mix.
   - PNIEC trends considering the biomass power plants, hydropower power plants and geothermal power plants.
   - Onshore and offshore wind potentials limitation.
   - Solar potential limitation.

  - Hydrogen system, with electrolyzer, fuel cell and hydrogen tank, as new storage technology.

3. Battery-Hydrogen scenario (BH):

  - Carbon-phase out by 2025 of the different fossil fuel technologies, with exception of the natural gas which is could be still considered in the future energy mix.
  - PNIEC trends considering the biomass power plants, hydropower power plants and geothermal power plants.
  - Onshore and offshore wind potentials limitation.
  - Solar potential limitation.
  - New storage technologies are considered, in particular both battery and hydrogen systems.

4.1 Representative days sensitivity analysis

Before implementing the final scenarios proposed, it is performed a sensitivity analysis considering a base battery scenario by 2040 in order to analyse the influence of the variation of the number of representative days (RDs) with respect to the final model output results.

It is chosen to develop this sensitivity analysis by means of a simplified Battery Base scenario by 2040. Indeed, the focus of this analysis is the resolution accuracy and thus it is done with a less complex system with respect to the one with the hydrogen storage technology scenario. Moreover, the clustering is performed using solar and wind onshore capacity factor values only. In fact, the clustering time representation is utilized to consider different specifics attributes for both the demand and supply sides, such as the electricity demand variation and the natural sources referred to wind and solar variation.

Nevertheless, by means of this method it is possible to assume a different number of representative days 6, 12, 24, 36, 48, 72, 144 and then 365 RDs. Increasing the number of representative days, the computational time increases and also the solution is more refined and less simplified. Therefore, it is necessary to identify the optimal number of representative days as a compromised between the computational time and the solution accuracy.

For this case study, the number of representative days analysed are 6, 12, 24, 36, 48, 72 and 144 RDs. Besides, the final output results which are analysed for each RDs case are the objective function and the main sizing outcomes, such as the total annual capacity and production by technology annual, as functions of RDs.

In particular, it is necessary to study the convergence of the different parameters computed by the model. As it is possible to appreciate from the figures 4.1, 4.2 and 4.3, the different parameters tend to converge to a stable value by increasing the number of RDs, though the variation with respect to 6 and 144 RDs is limited.

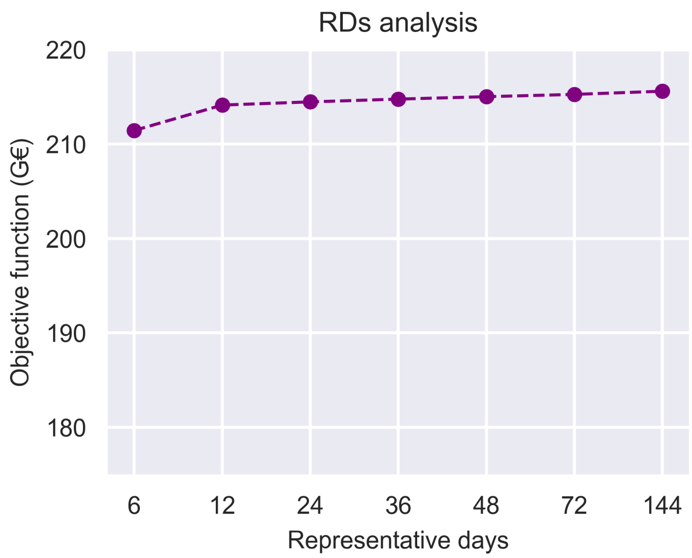

Figure 4.1: Objective function from RDs analysis.

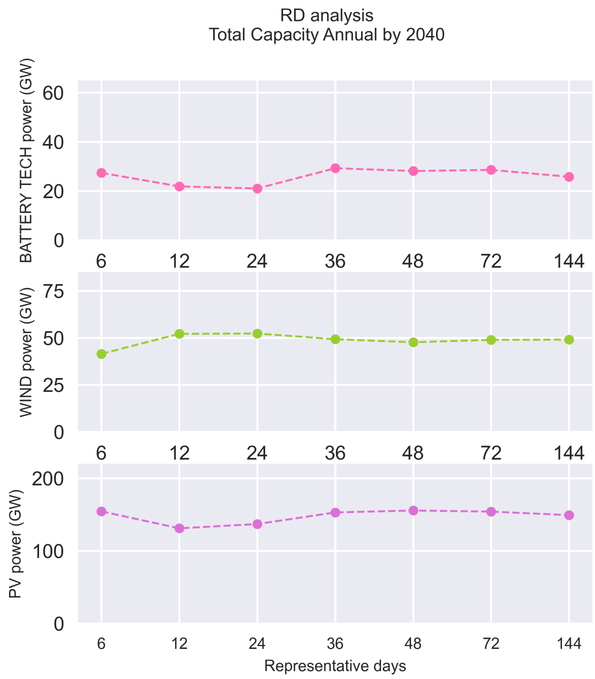

Figure 4.2: Total annual capacity by 2040 from RDs analysis.

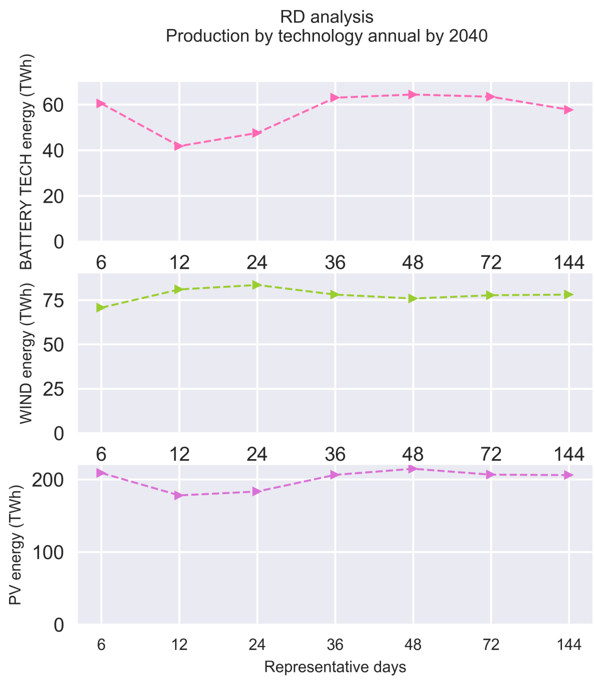

Figure 4.3: Production by technology annual by 2040 from RDs analysis.

The computational time is the other parameter which is considered, in order to identify the optimal choice of RDs. As shown in the figure 4.4, the higher the number of RDs the higher data processing. However, even using the Battery simplified scenario by 2040 it was not possible to obtain a result due to the high virtual memory requested.

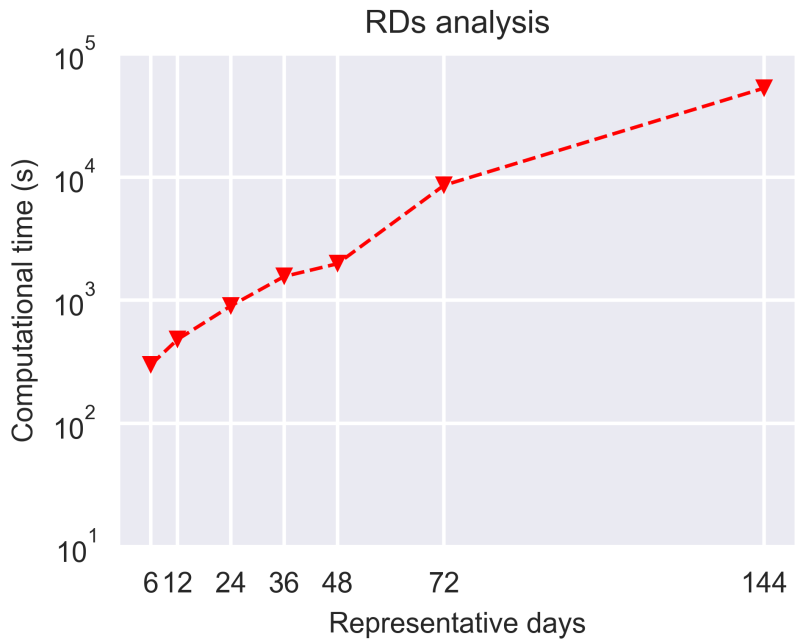

Figure 4.4: Computational time from RDs analysis.

Nevertheless, for this case study, long-term scenarios by 2050 are elaborated, therefore 6 RDs are chosen to perform the different analysis.

Chapter 5

Results analysis

The Italian energy system is simulated in order to estimate the optimal configuration, by means of the various scenarios. Storage systems are differentiate in the three main scenarios to highlight their different role. Besides each scenario is elaborated considering the two different computed photovoltaic and onshore wind potential limitations in the *soft* case. The main output results which are analyzed are the power and storage capacity, electricity production and finally the CO_2 emissions.

Subsequently, those parameters are compared in specific years (2030, 2040 and 2050) analyzing the different scenario output. Furthermore, the *extreme* case limitations for onshore wind and photovoltaic systems are applied to the three different scenarios, and then compared to the *soft* case.

Finally, it is performed a specific analysis for the *soft* case battery-hydrogen (BH) scenario developing a NPC-emission Pareto curve in order to better analyse the hydrogen storage role.

5.1 Storage facilities scenarios analysis

The net present costs (NPC), which is the objective function of the energy model, of the different scenarios are shown in table 5.1. The hybrid scenario is the most effective configuration with a NPC equal to 291.38 G€, followed by the only-hydrogen case and then the only-battery case with a NPC of 291.40 G€.

Table 5.1: Net present cost for only-battery, only-hydrogen and battery-hydrogen scenarios.

	Objective function (G€)
OB	291.40
OH	294.29
BH	291.38

Nevertheless, it is interesting to notice that the NPC between the three cases is not so difference, indeed in order to cover the same electricity demand increase, it is proposed VRES systems installation coupled with the different storage technologies available.

5.1.1 Only-Battery scenario

The total annual capacity shown in the figure 5.1 represents the capacity evolution of the different technologies. Photovoltaic and onshore wind energy systems face a huge increase, leading to a high renewable penetration in the energy mix equal to 82.7% by 2050. This is due to the fact that geothermal and hydro-power plant maximum capacity values are limited due to a source saturation in Italy, and also bioenergies are prospected to not increase in the future, as planned in the NECP. In particular, onshore wind and PV systems amounts to 77.0 GW and 190.8 GW respectively by 2050.

The production by technology annual shown in figure 5.2 represents the evolution

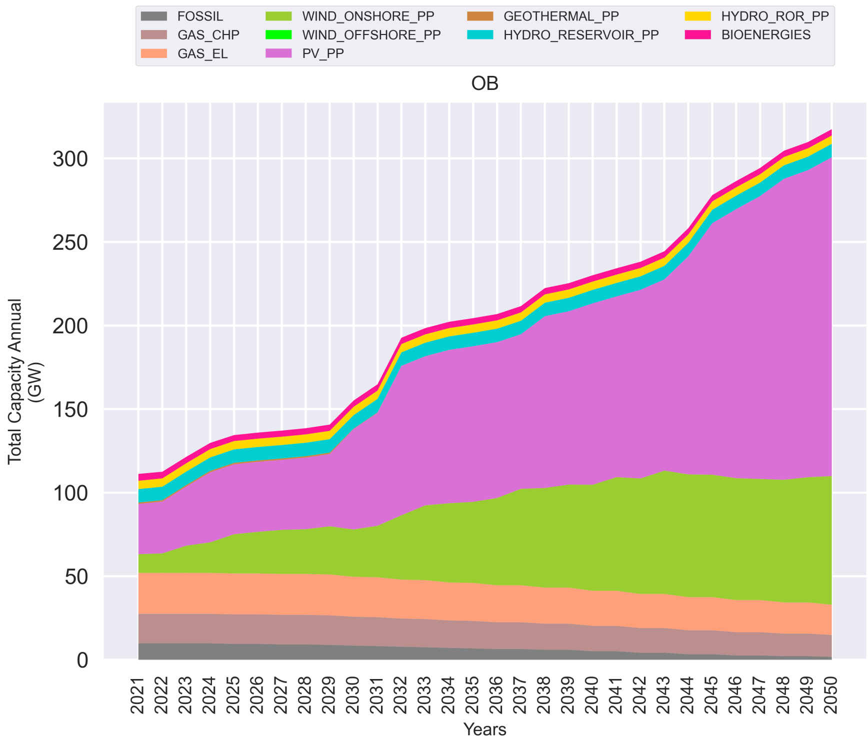

Figure 5.1: Total annual capacity OB scenario.

in the electricity production during the model period 2021-2050. Renewable technologies such as onshore wind systems, PV systems and hydro-power plant are the main contributors in the electricity production representing the 88.0% in the final electricity mix by 2050, where the VRES represents the 69.5% by 2050, as shown in figure 5.3. The residual part of the electricity production relies on gas-base power plants, with a total share of 12.0% by 2050.

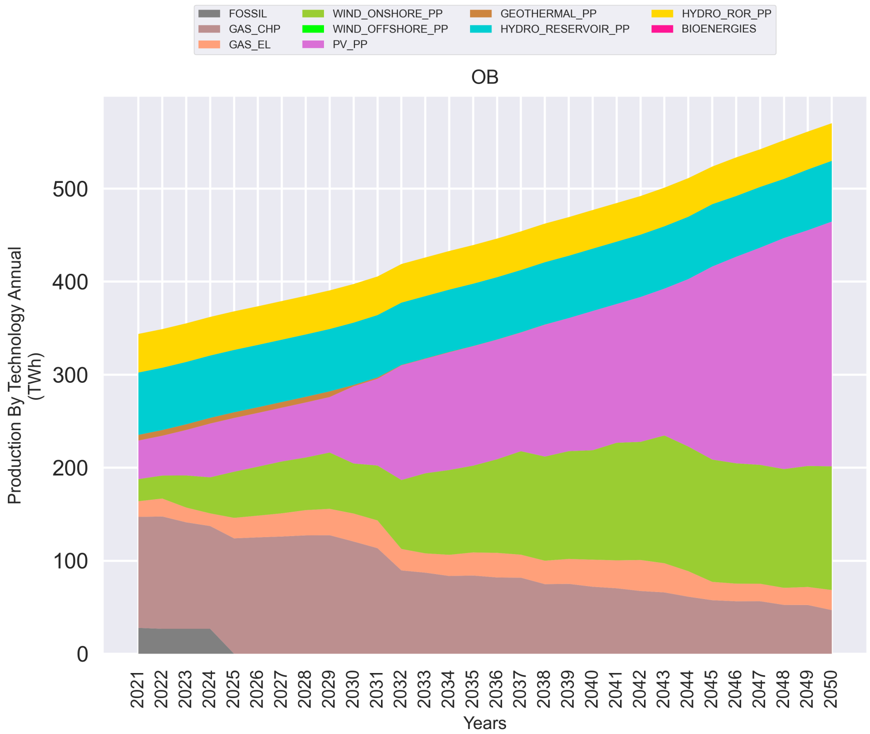

Figure 5.2: Production by annual technology OB scenario.

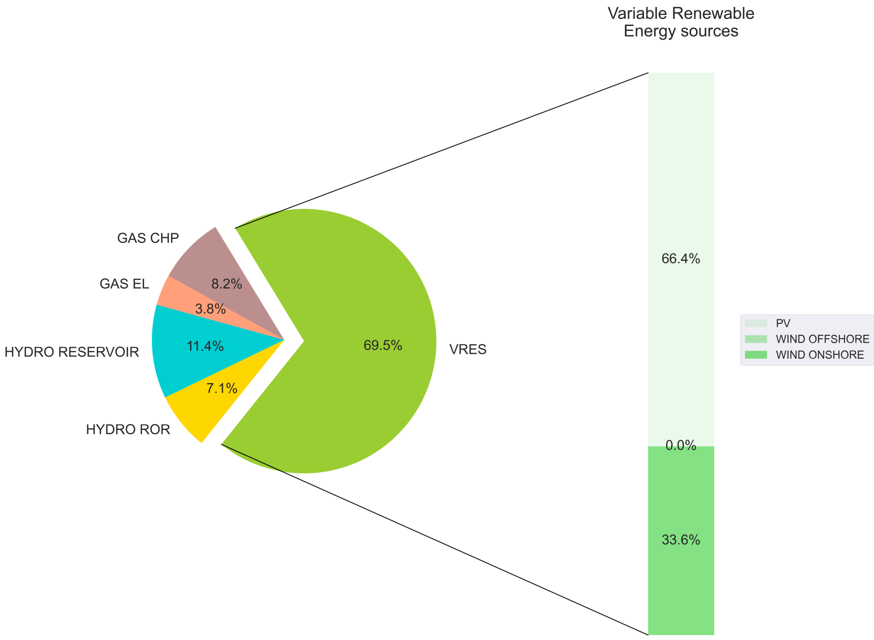

Figure 5.3: Electricity production by 2050 plot OB.

In addition, as it possible to see figures 5.4 and 5.5, there is a direct correspondence between the renewable system and the storage facilities expansions. Indeed, the battery storage technology faces a huge capacity increase from 2030, when the total onshore wind a PV capacity is equal to 88.5 GW. Thus, the key role of storage technology is highlighted as systems coupled with VRES in order to avoid their oversizing and allow a complete exploitation of their electricity production, dealing also with overproduction and intermittent behaviour. The battery power- and energy- component capacity are equal to 98.0 GW and 196.1 GWh by 2050.

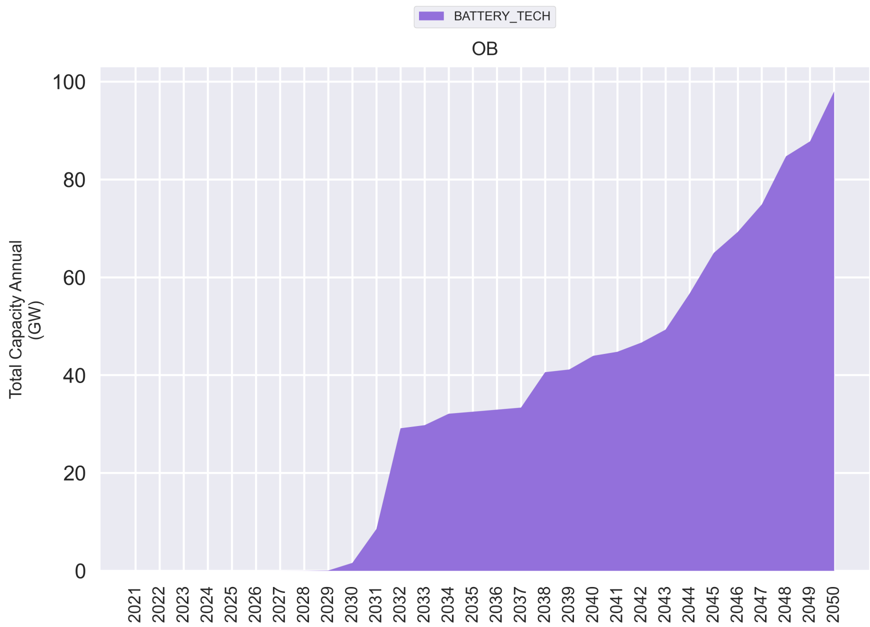

Figure 5.4: Total annual capacity battery power-component OB.

As shown in figure 5.5, the battery energy-component is sized considering the energy-to-power ratio range between 0.5 and 2, coherent with the Li-ion battery technology features.

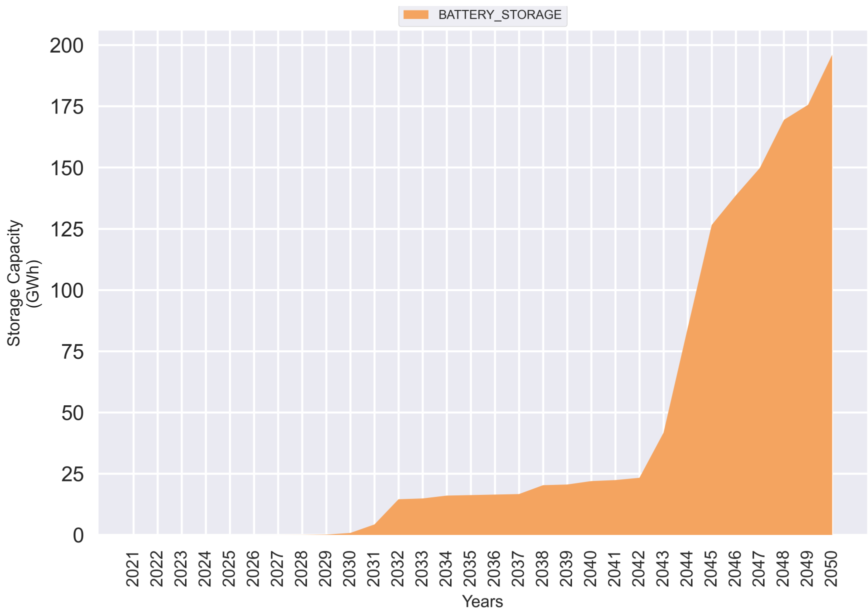

Figure 5.5: Total annual capacity battery energy-component OB.

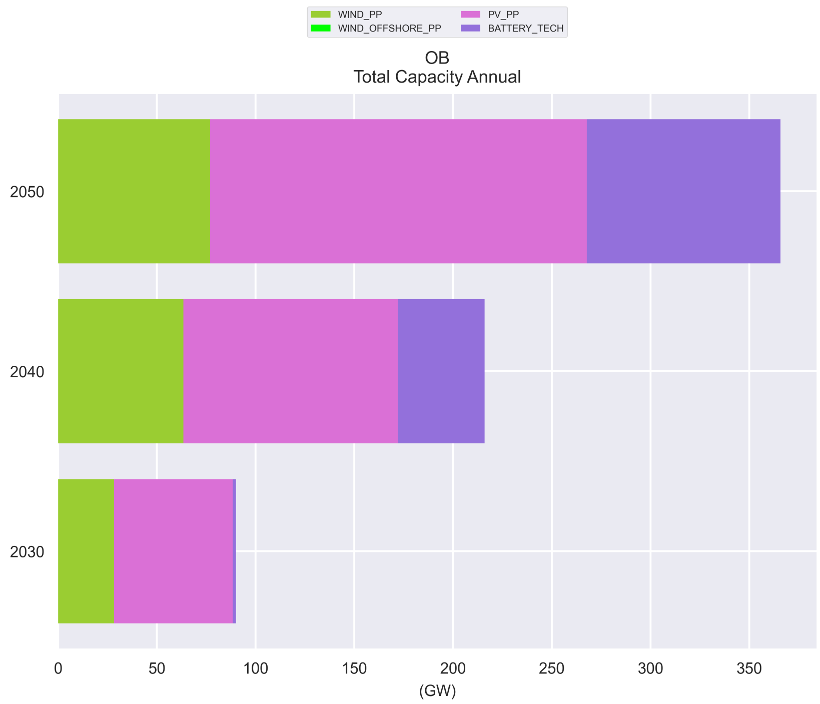

Figure 5.6: Total annual capacity comparison by 2030-2040-2050 plot OB.

Besides, the total annual capacity for onshore wind, PV systems and battery power- component is analyzed for three main years (2030, 2040, 2050), as shown in figure **??**. Indeed, comparing the years 2030 and 2050, onshore wind and PV systems capacity increases from 28.3 GW and 60.2 GW respectively to 77.0 GW and 190.8 GW, while the battery power- component capacity changes from 1.6 GW to 98.0 GW. Therefore, the battery storage role is proven for high renewable penetration, when it becomes more convenient to couple VRES with storage facilities, in order to better deal with them.

5.1.2 Only-Hydrogen scenario

The total annual capacity shown in the figure 5.7 represents the capacity evolution of the different technologies. Photovoltaic and onshore wind energy systems face a huge increase, leading to a high renewable penetration in the energy mix equal to 81.0% by 2050. This is due to the fact that geothermal and hydro-power plant maximum capacity values are limited due to a source saturation in Italy, and also bioenergies are prospected to not increase in the future, as planned in the NECP. In particular, onshore wind and PV systems amounts to 78.5 GW and 159.0 GW respectively by 2050.

The production by technology annual shown in figure 5.8 represents the evolution

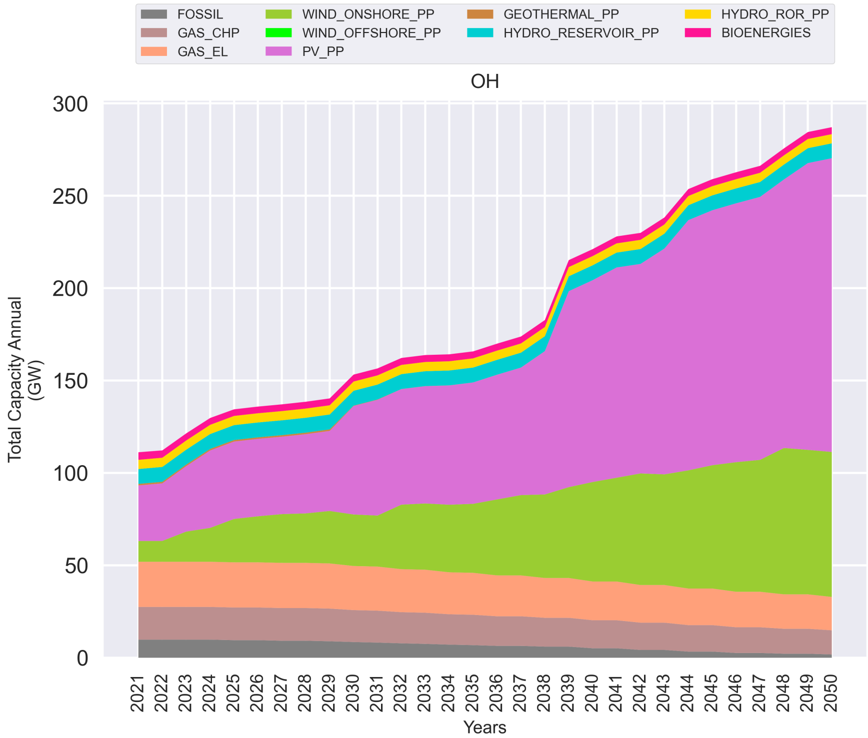

Figure 5.7: Total annual capacity OH scenario.

in the electricity production during the model period 2021-2050. Renewable technologies such as onshore wind systems, PV systems and hydro-power plant are the main contributors in the electricity production representing the 85.7% in the final electricity mix by 2050, where the VRES represents the 65.8% by 2050, as shown in figure 5.9. The residual part of the electricity production relies on gas-base power plants, with a total share of 14.3% by 2050.

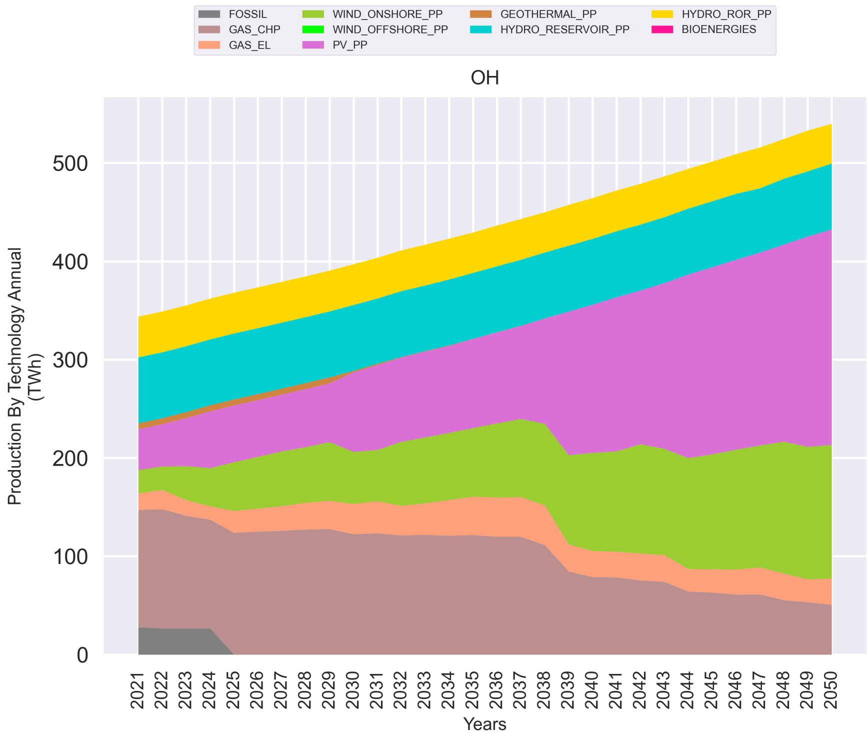

Figure 5.8: Production by annual technology OH scenario.

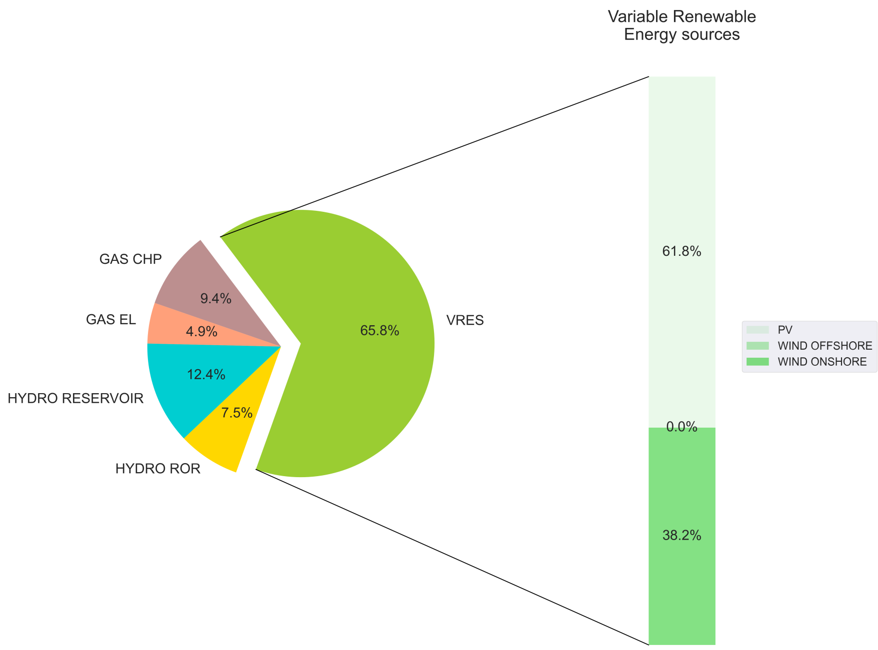

Figure 5.9: Electricity production by 2050 plot OH.

In addition, as it possible to see figures 5.10 and 5.11, there is a direct correspondence between the renewable system and the storage facilities expansions. Indeed, the hydrogen storage capacity components increase from 2038, where in particular there is a huge expansion of the PV capacity which increases from 69.0 GW in 2037 to 77.5 GW in 2038, up to 2050 when electrolyzer capacity is equal to 34.2 GW, the fuel cell amounts 9.0 GW and the hydrogen tank is equal to 259.9 GWh.

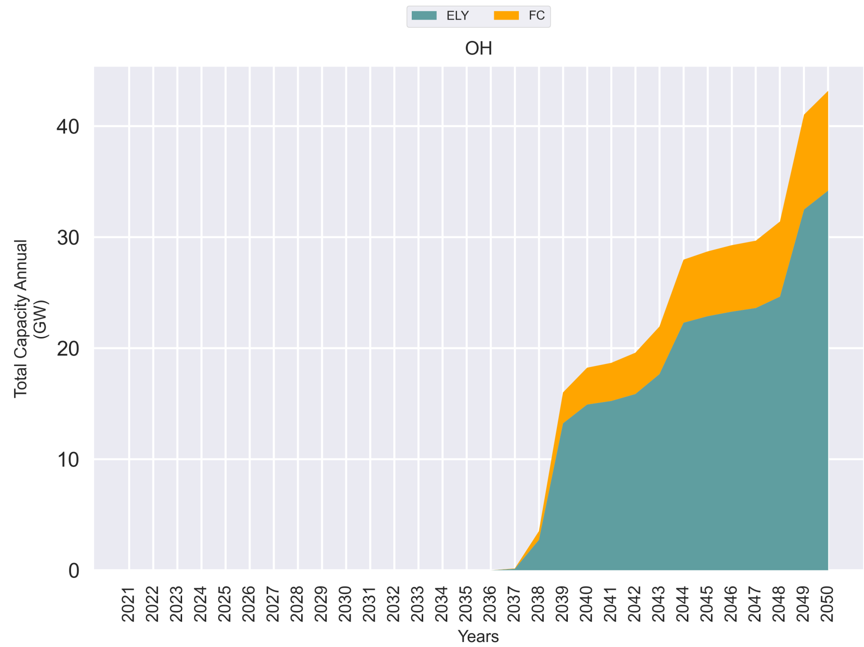

Figure 5.10: Total annual capacity electrolyzer and fuel cell components OH.

The figure 5.11 shows the hydrogen tank increase which follows both the electrolyer and fuel cell evolutions.

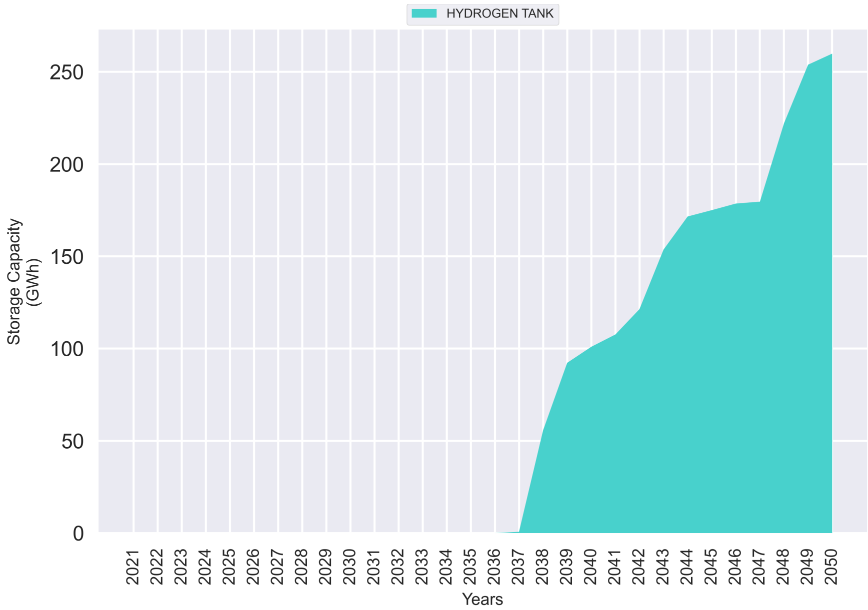

Figure 5.11: Total annual capacity hydrogen tank OH.

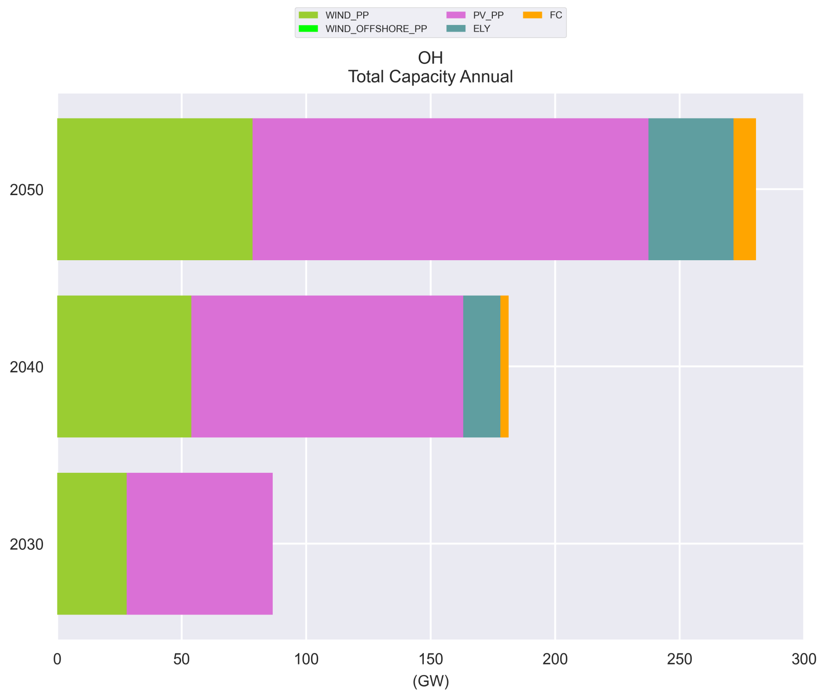

Figure 5.12: Total annual capacity comparison by 2030-2040-2050 plot OH.

Besides, the total annual capacity for onshore wind, PV systems, electrolyzer and fuel cell is analyzed for three main years (2030, 2040, 2050), as shown in figure 5.12. Indeed, comparing the years 2030 and 2050, onshore wind and PV systems capacity increases from 27.9 GW and 58.7 GW respectively to 78.5 GW and 159.0 GW, while the electrolyzer and fuel cell capacity changes from 0 GW to 34.2 GW and 9.0 GW respectively. Therefore, hydrogen technology become cost-effective and convenient only for high VRES share, due to its high costs and low efficiency.

5.1.3 Battery-Hydrogen scenario

The total annual capacity shown in the figure 5.7 represents the capacity evolution of the different technologies. Photovoltaic and onshore wind energy systems face a huge increase, leading to a high renewable penetration in the energy mix equal to 82.8% by 2050. This is due to the fact that geothermal and hydro-power plant maximum capacity values are limited due to a source saturation in Italy, and also bioenergies are prospected to not increase in the future, as planned in the NECP. In particular, onshore wind and PV systems amounts to 73.7 GW and 195.5 GW respectively by 2050.

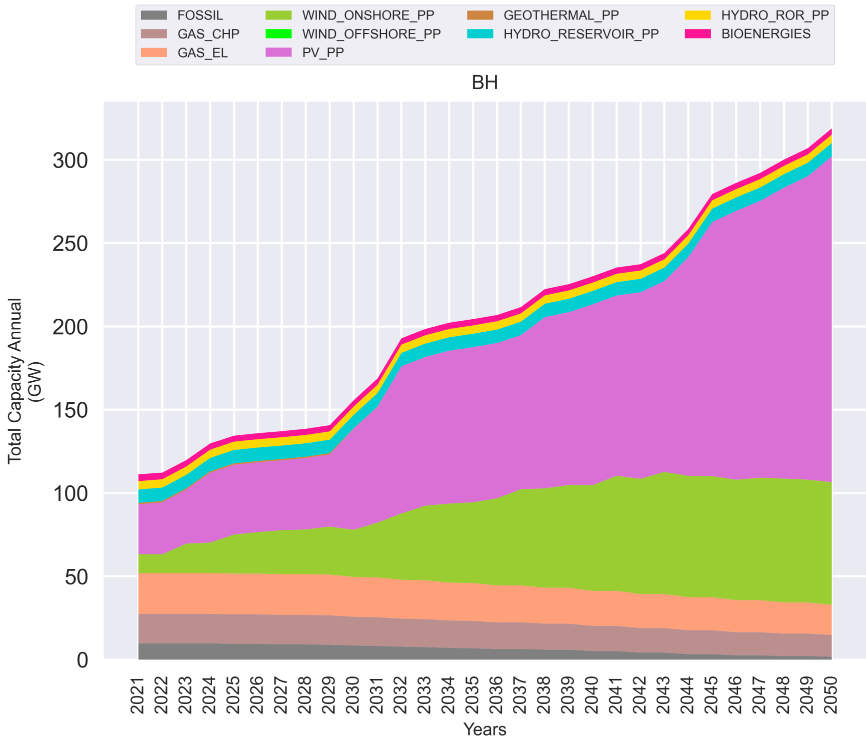

Figure 5.13: Total annual capacity BH scenario.

The production by technology annual shown in figure 5.14 represents the evolution in the electricity production during the model period 2021-2050. Renewable technologies such as onshore wind systems, PV systems and hydro-power plant are the main contributors in the electricity production representing the 89.5% in the final electricity mix by 2050, where the VRES represents the 70.6% by 2050, as shown in figure 5.9. The residual part of the electricity production relies on gas-base power plants, with a total share of 10.5% by 2050.

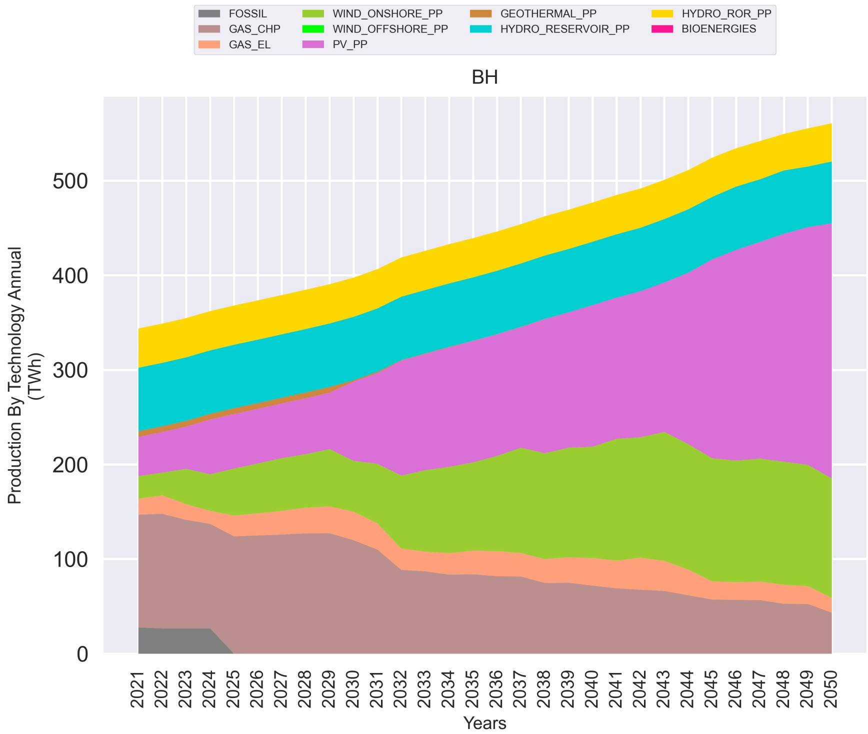

Figure 5.14: Production by annual technology BH scenario.

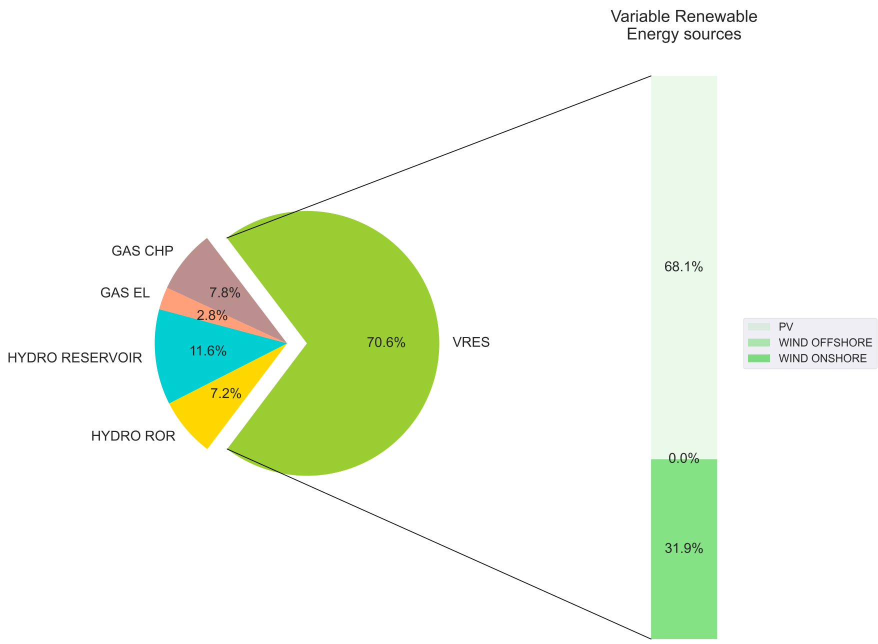

Figure 5.15: Electricity production by 2050 plot BH.

In addition, as it possible to see figures 5.16 and 5.17, there is a direct correspondence between the renewable system and the storage facilities expansions. Indeed, the hydrogen storage capacity components increase from 2038, where in particular there is a huge expansion of the PV capacity which increases from 69.0 GW in 2037 to 77.5 GW in 2038, up to 2050 when electrolyzer capacity is equal to 34.2 GW, the fuel cell amounts 9.0 GW and the hydrogen tank is equal to 259.9 GWh.

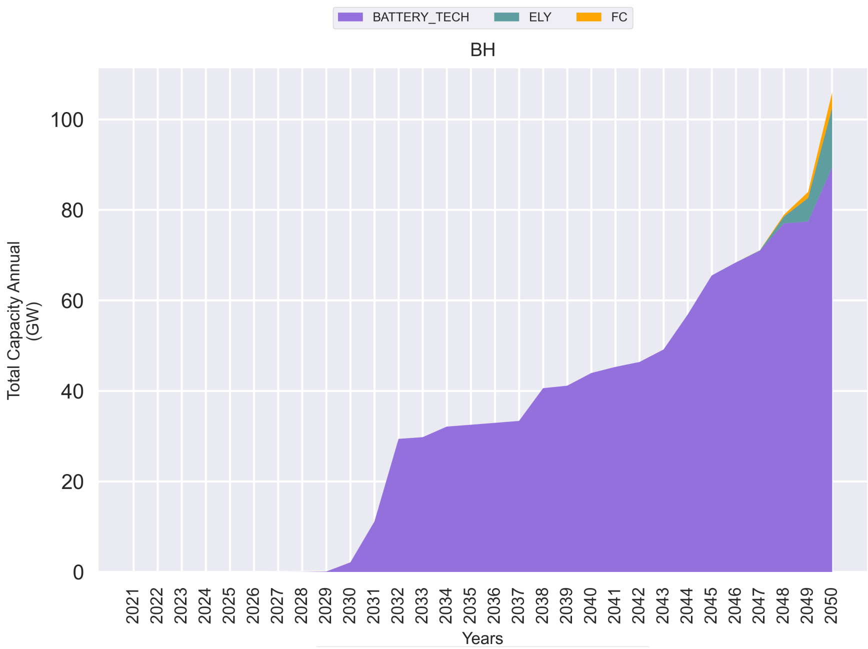

Figure 5.16: Total annual capacity electrolyzer, fuel cell and battery power- components BH.

The figure 5.17 shows both the hydrogen tank increase, which follows both the electrolyer and fuel cell evolutions, and the battery energy-component, which is sized considering the energy-to-power ratio range between 0.5 and 2, coherent with the Li-ion battery technology features.

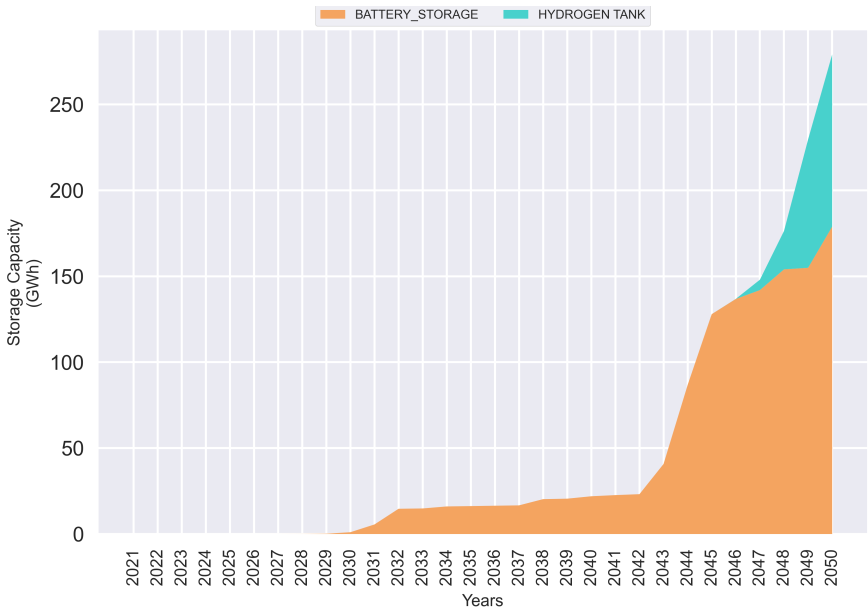

Figure 5.17: Annual capacity hydrogen tank and battery energy- components BH.

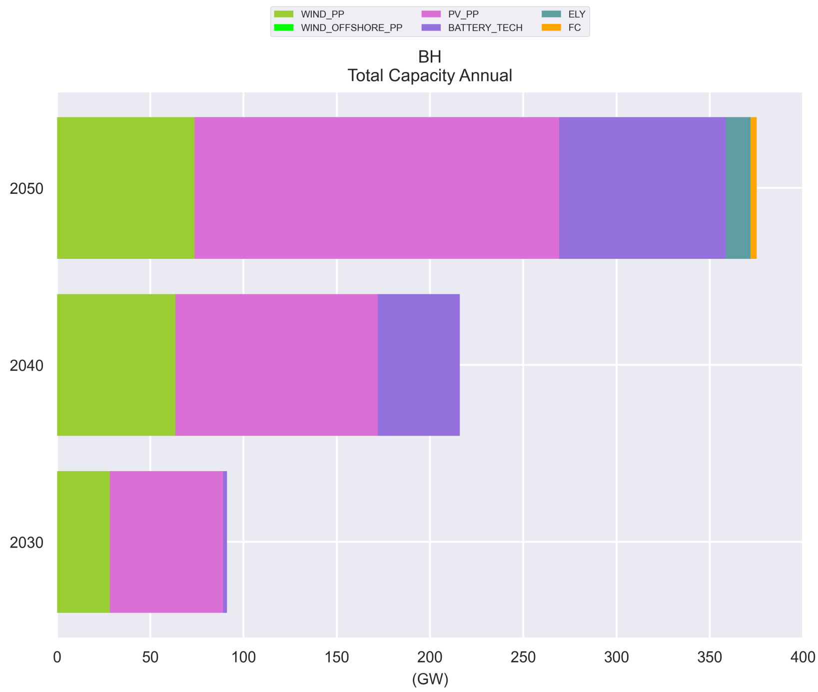

Figure 5.18: Total annual capacity comparison by 2030-2040-2050 plot BH.

Besides, the total annual capacity for onshore wind, PV systems, electrolyzer, fuel cell and battery power-component is analyzed for three main years (2030, 2040, 2050), as shown in figure 5.18. Indeed, comparing the years 2030 and 2050, onshore wind and PV systems capacity increases from 28.3 GW and 60.7 GW respectively to 73.7 GW and 195.5 GW, while the electrolyzer and fuel cell capacity changes from 0 GW to 13.2 GW and 3.4 GW respectively and the battery power-component from 2.1 GW to 89.5GW by 2050. Therefore, the battery technology is the most suggested technology thanks to its high efficiency with respect to the hydrogen storage technology. Indeed, hydrogen technology becomes cost-effective and convenient only for high VRES share, due to its high costs and low efficiency.

Figures 5.19 and 5.20 shows VRES and storage technologies capacity installed by 2050. Battery technology still plays the main role in term of storage facility and is equal to 89.5 GW in the BH scenario, though the necessary electrolyzer and fuel cell capacity to face a comparable VRES size are equal to 13.2 GW ans 3.4 GW respectively, thanks to high-capacity hydrogen tanks feature.

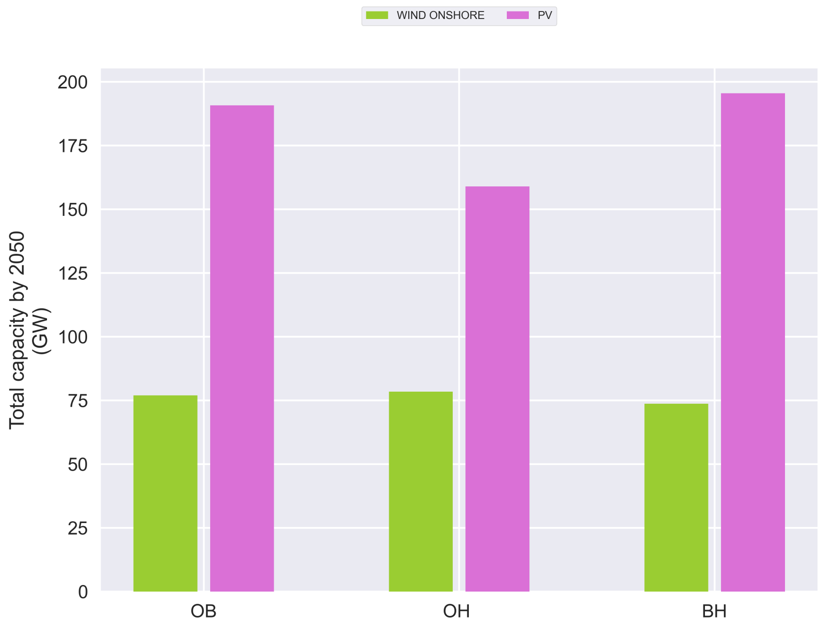

Figure 5.19: Total capacity installed by 2050 for OB, OH, BH scenarios.

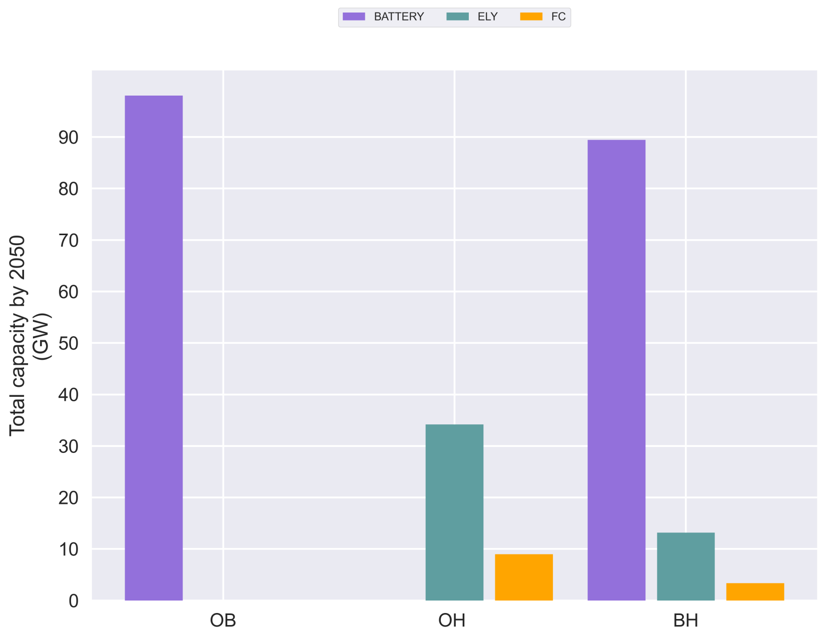

Figure 5.20: Total capacity for storage technologies installed by 2050 for OB, OH, BH scenarios.

5.2 *Extreme* and *soft* case scenarios comparison

As explained in chapter 3, there are different factors limiting the installation of new renewable systems and also there is not a defined and standardized method to estimate their potentials. Therefore, it is performed the same storage facilities analysis also for the *extreme* case and then compared with the *soft* case.

As shown in the figures 5.21 and 5.22, both onshore and offshore wind and photovoltaic renewable systems are installed the three different scenarios. Indeed, the flexibility of the model is limited with respect to the *soft* case: both onshore wind and PV potentials are saturated and therefore also offshore wind technology is installed. In particular, in the *extreme* case by 2050 for the three different scenarios onshore wind PV systems amounts to 26.5 GW and 127 GW respectively, while offshore wind system capacity is equal to 34.6 GW for OB, 36.4 GW for OH and 36.4 GW.

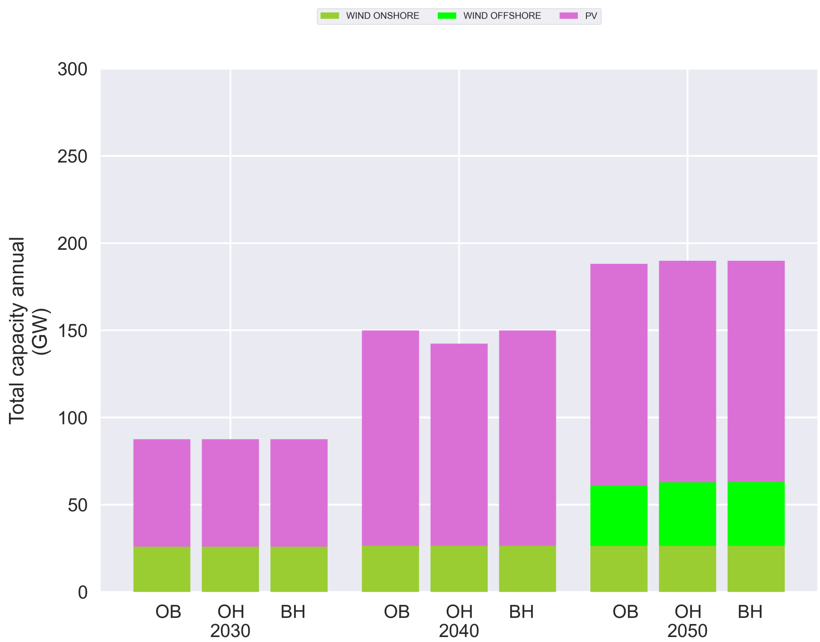

Figure 5.21: VRES Capacity for *extreme* case.

In figure 5.22, VRES total annual capacity installed for the same main years (2030, 2040, 2050) is shown. The higher potentials for onshore wind and PV allow a major exploitation of those sources.

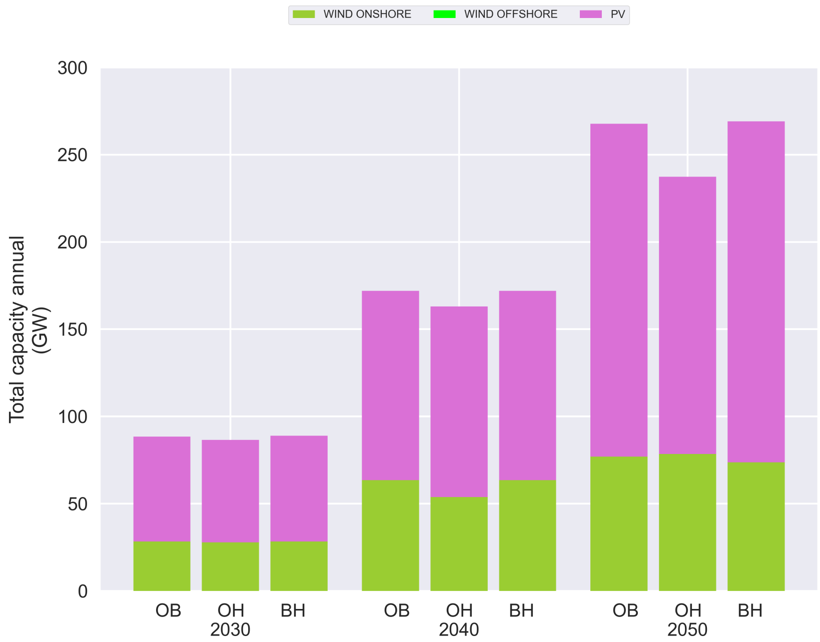

Figure 5.22: VRES Capacity for *soft* case

Besides, due to the lower amount of new VRES capacity installed in the *extreme* case, also the storages technologies face a poor increase with respect to the *soft* case, as shown in figure 5.23 and 5.24. Nevertheless, it is interesting to notice that by 2050, in the hybrid scenarios though the total new VRES capacity (189.9 GW) is comparable and equal with OB (188.1 GW) and OH (189.8 GW) scenarios respectively, the amount of new battery technology installed is equal to 20.2 GW and thus is lower with respect to 2030.

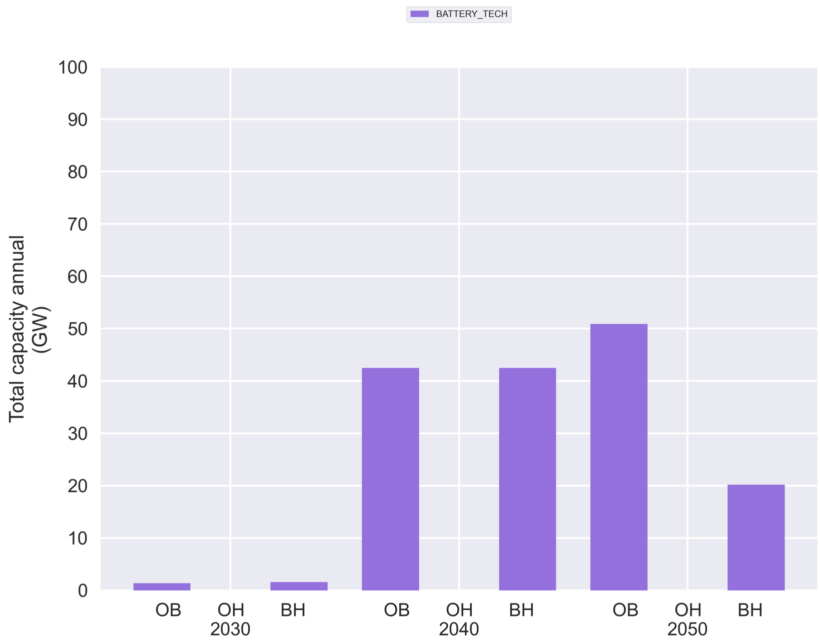

Figure 5.23: Battery capacity for *extreme* case.

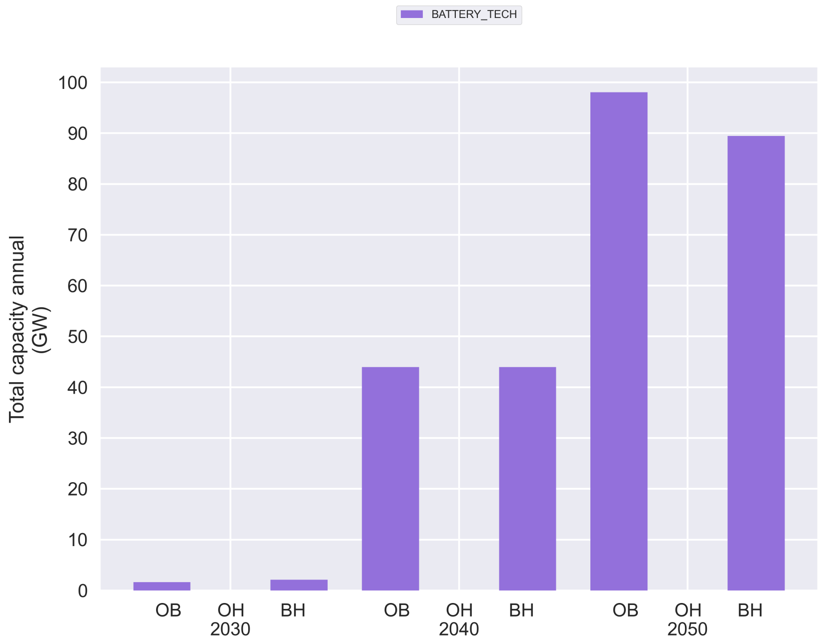

Figure 5.24: Battery capacity for *soft* case

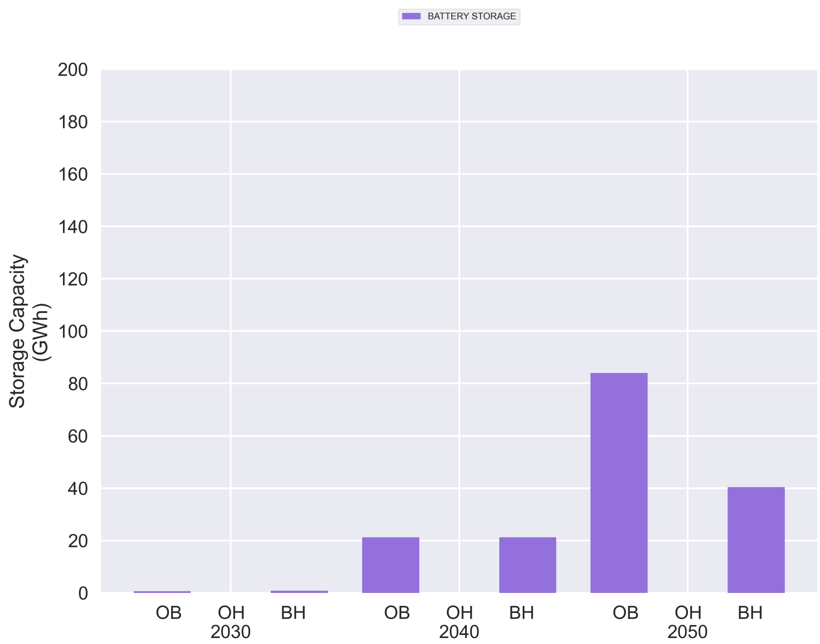

Figure 5.25: Battery storage capacity for *extreme* case.

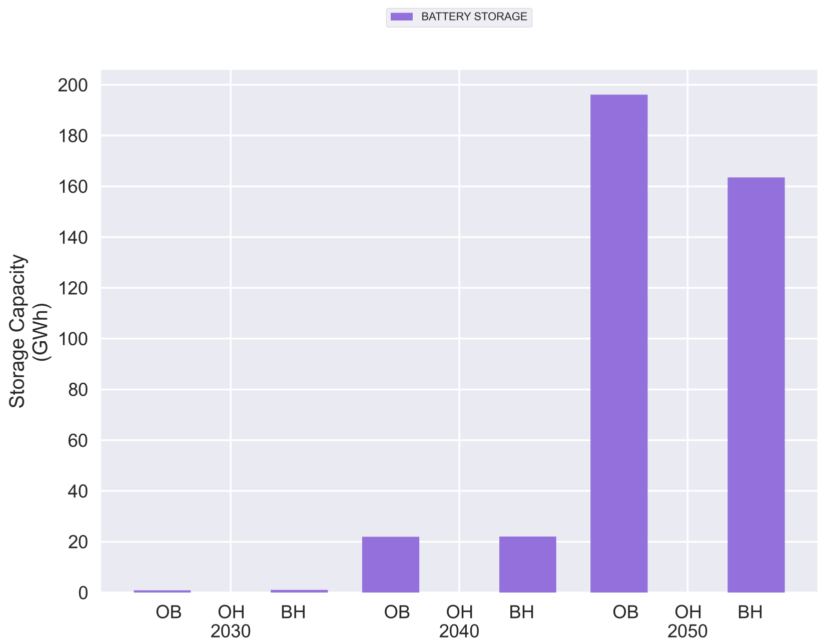

Figure 5.26: Battery storage capacity for *soft* case.

Figures 5.25 and 5.26 show the battery energy-component capacity installed in the three main years (2030, 2040, 2050), which is sized considering the energy-to-power ratio range between 0.5 and 2, coherent with the Li-ion battery technology features. In addition, for the BH scenario in the *soft* case it possible to notice that by 2050 the battery storage technology still plays the main role, compared to the BH scenario in the *extreme* case.

Figures 5.27 and 5.28 show electrolyzer and fuel cell capacity installed in the main three years (2030, 2040, 2050) for *extreme* and *soft* cases. Also for those technologies the increase is more limited for the *extreme* case with respect to the *soft* one. Indeed, in the *extreme* case for the OH scenario electrolyzer and fuel cell capacities are equal to 21.7 GW and 6.1 GW respectively, while for the *soft* case, electrolyzer and fuel cell capacity reaches 34.2 GW and 9.0 GW for BH scenario they are equal to 14.6 GW and 3.9 GW.

Nevertheless, it is interesting to highlight that for the *extreme* case BH scenario, electrolyzer and fuel cell capacity reaches 14.6 GW and 3.9 GW respectively, and in the *soft* case they are equal to 13.2 GW and 3.4 GW. Therefore, for the hybrid configuration the hydrogen storage capacities are comparable, showing that for the extreme case, this technology has the main role as storage facility used.

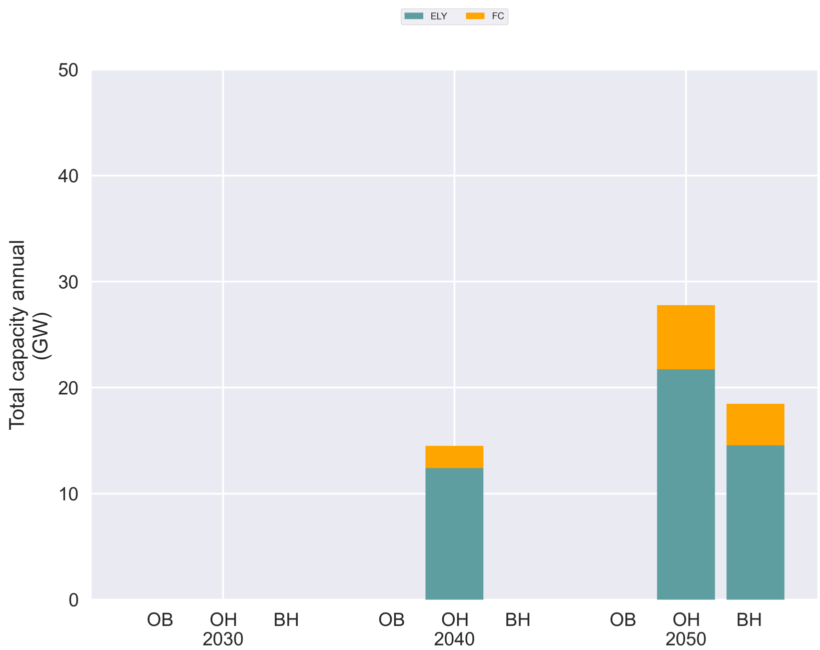

Figure 5.27: Electrolyzer and fuel cell capacity for *extreme* case.

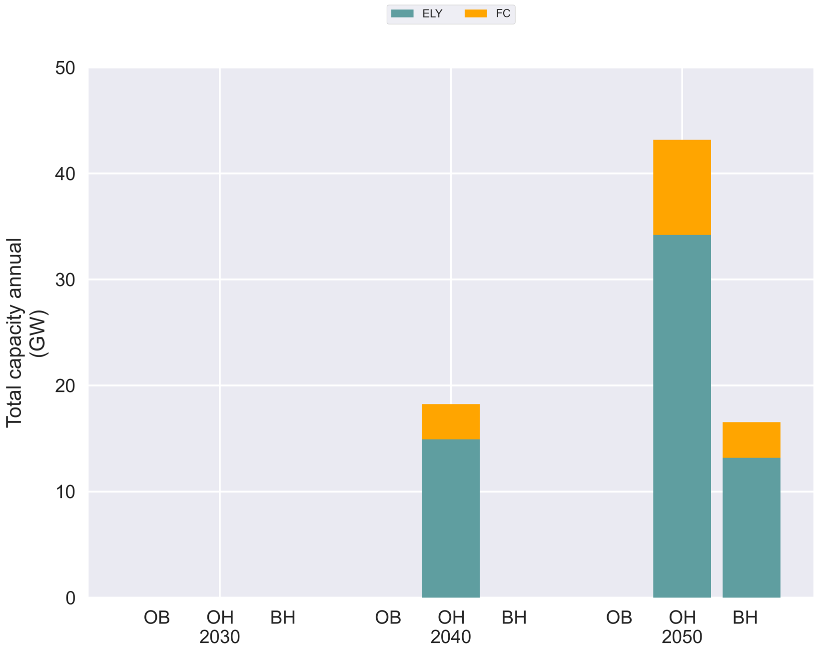

Figure 5.28: Electrolyzer and fuel cell capacity for *soft* case.

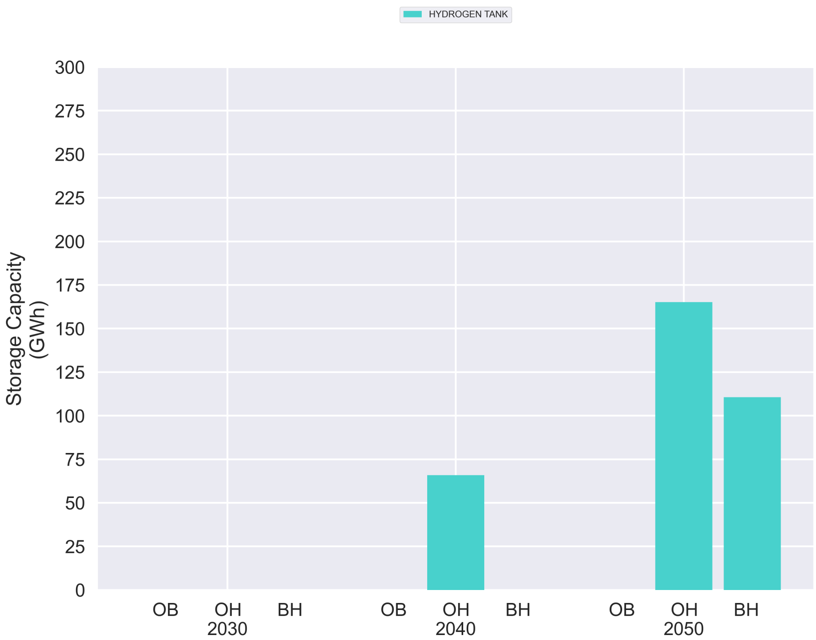

Figure 5.29: Hydrogen tank capacity for *extreme* case.

Figures 5.29 and 5.30 show the hydrogen tank capacity installed which has a coherent behaviour with respect to the electrolyzer and fuel cell capacities suggested. In the *extreme* case by 2050 for OH scenario hydrogen tank capacity is equal to 165.2 GWh, and for BH is equal to 110.6 GWh.

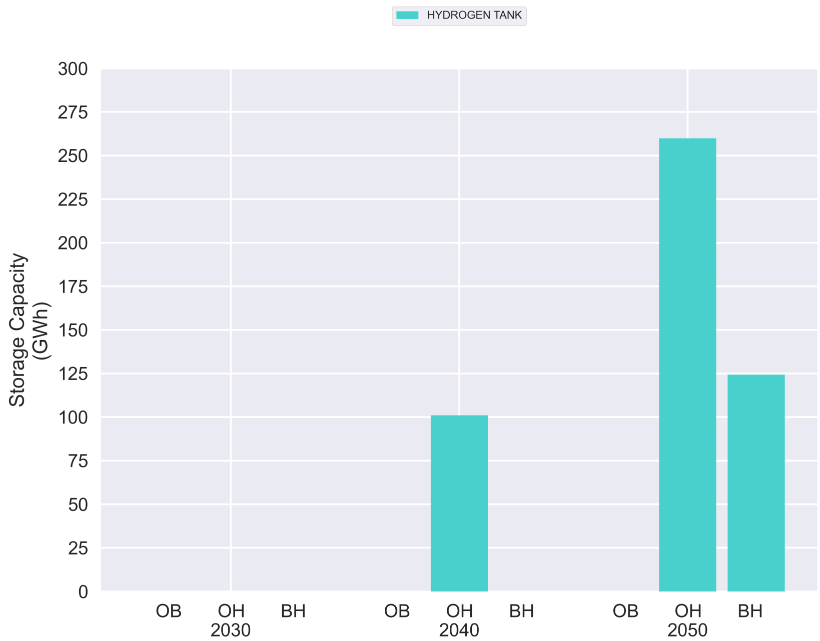

Figure 5.30: Hydrogen tank capacity for *soft* case.

In figures 5.31 and 5.32, the different storages technologies are summarized for both the *soft* and *extreme* case. Due to the *extreme* onshore wind and PV potential limitation, also the storage technologies shows a poor increase with respect to the *soft* case where there is a higher VRES penetration and therefore also battery and hydrogen technologies are suggested to be coupled.
In the hybrid scenarios though the total new VRES capacity is comparable with OB and OH scenarios, the amount of new battery technology installed is lower with respect to 2030, compensated by new hydrogen storage technology installed. Indeed, hydrogen tanks low-cost and high-capacity assumes a more important role. On the contrary, with the *soft* case, by 2050 battery technology still plays the major role, showing that hydrogen technology is still not advantageous though the higher VRES new capacity installed.

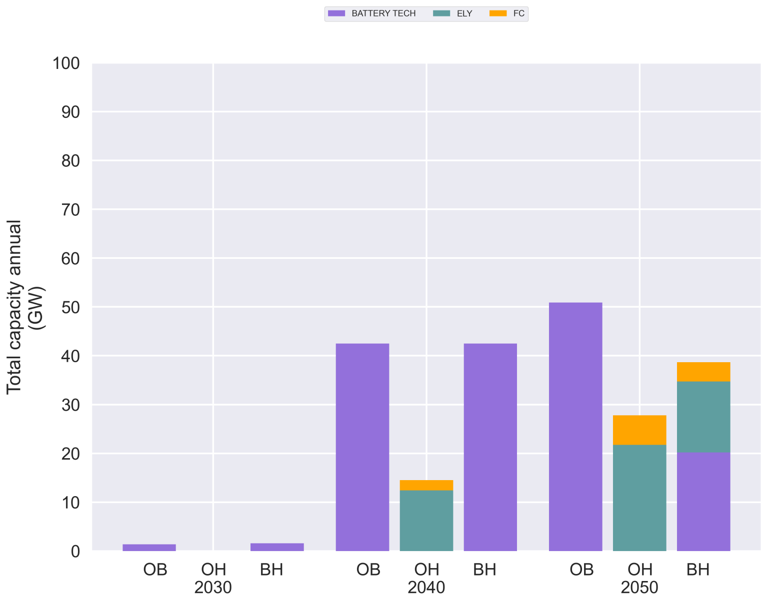

Figure 5.31: Total capacity electrolyzer, fuel cell and battery power-component for *extreme* case.

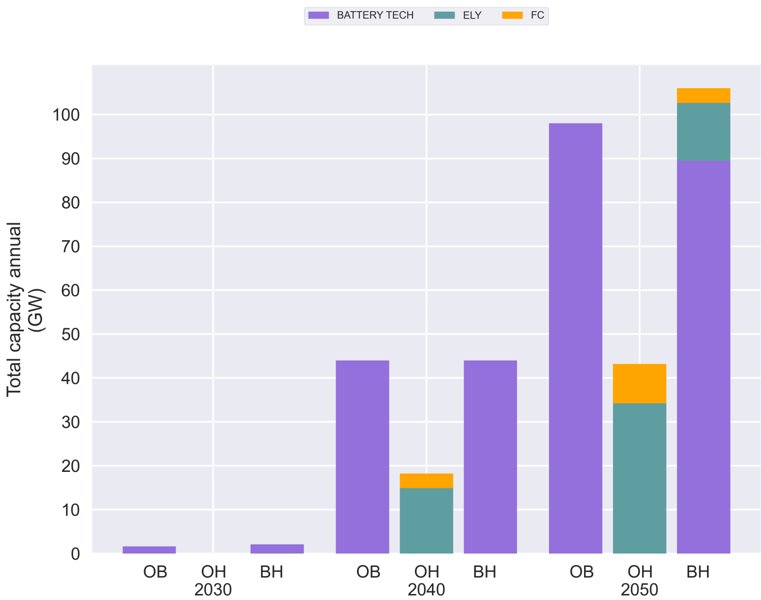

Figure 5.32: Total capacity electrolyzer, fuel cell and battery power-component for *soft* case.

In figures 5.33, 5.34 and 5.35 considering the electricity production side, due to the lower VRES capacity available, the main role is still played by onshore wind, PV systems also combined with offshore wind technology. However, part of the electricity generation is sustained by a higher share of gas based power plants.

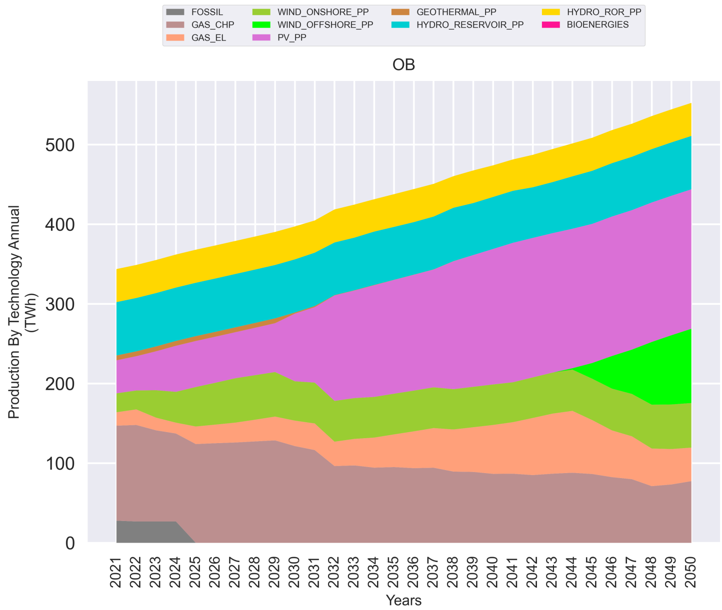

Figure 5.33: Electricity production for OB scenario.

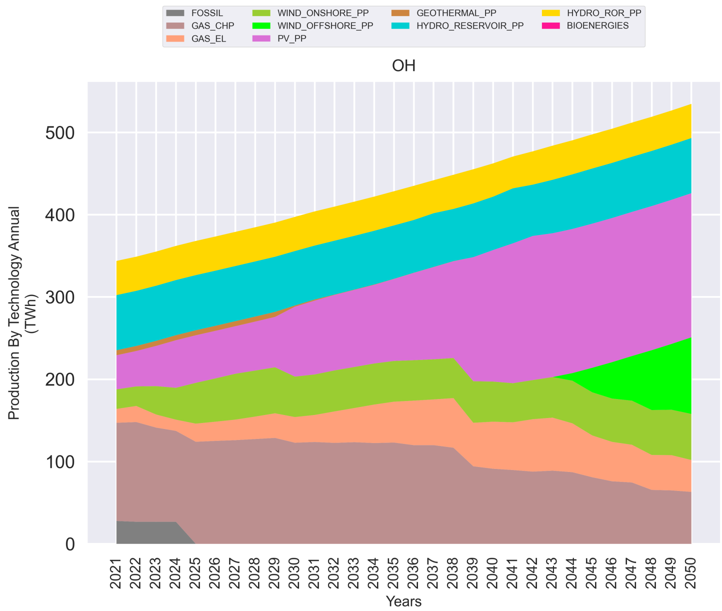

Figure 5.34: Electricity production for OH scenario.

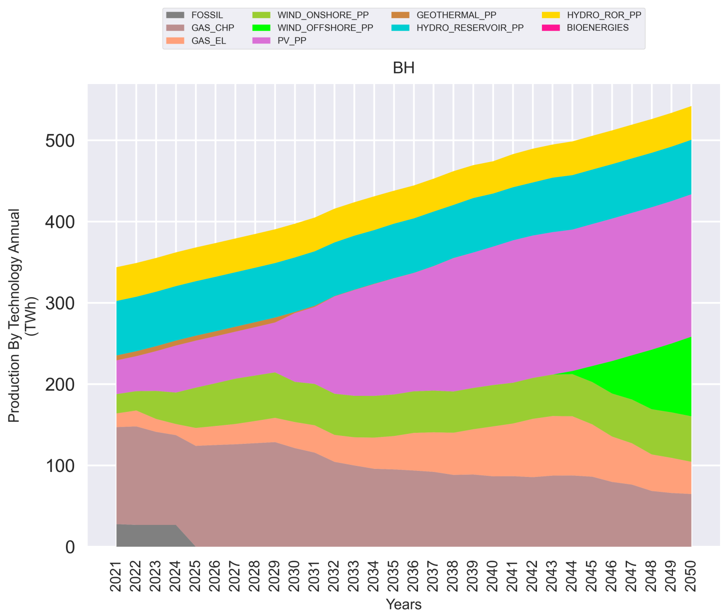

Figure 5.35: Electricity production for BH scenario.

Figures 5.36, 5.37 and 5.38 show the different electricity production pie by 2050. In *extreme* case a higher portion of electricity production relies on gas and it is equal to 21.6% for OB, 19.1% for OH and 19.3% for BH. The VRES contribution in the final electricity mix is equal to 58.7% for OB, 60.7% for both OH and BH scenarios. Therefore, compared to the *soft* case there is a decrease in the VRES contribution for the electricity production of about 10% less and an increase in the gas-based production of more than the double.

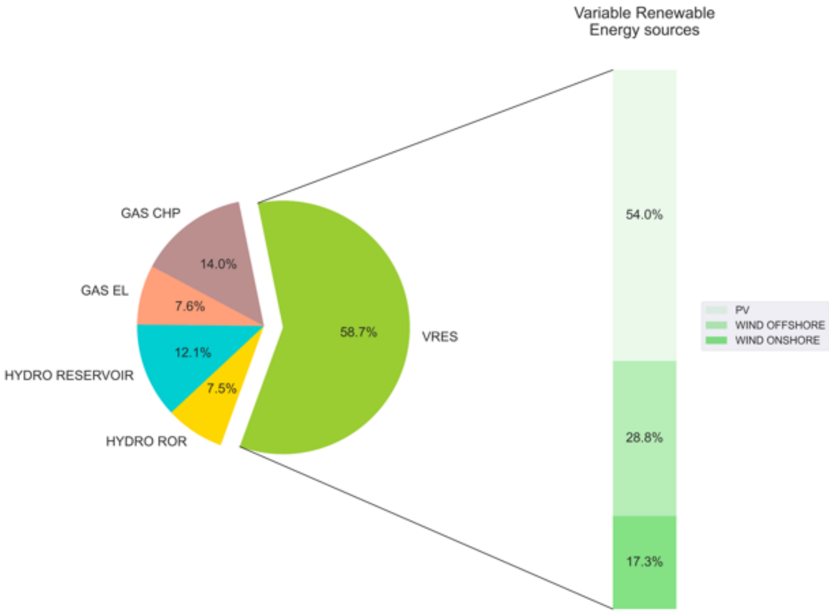

Figure 5.36: Electricity production by 2050 for OB scenario.

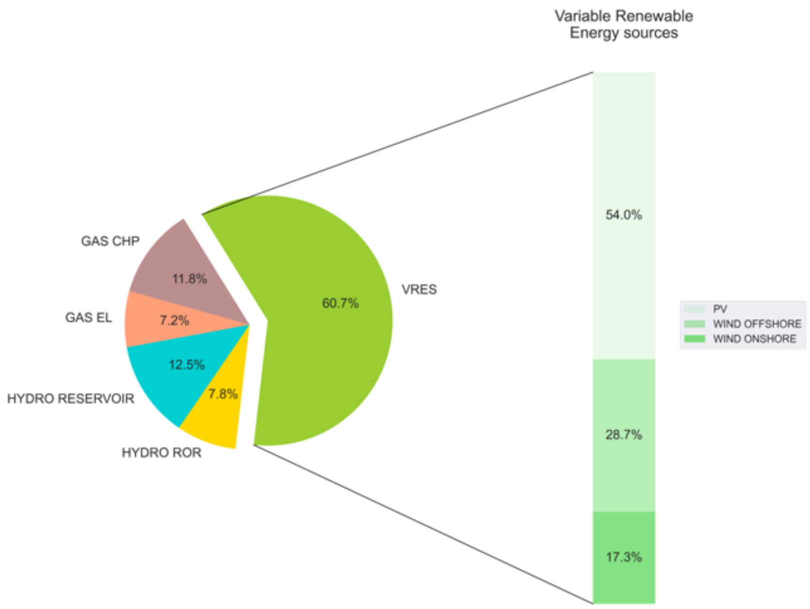

Figure 5.37: Electricity production by 2050 for OH scenario.

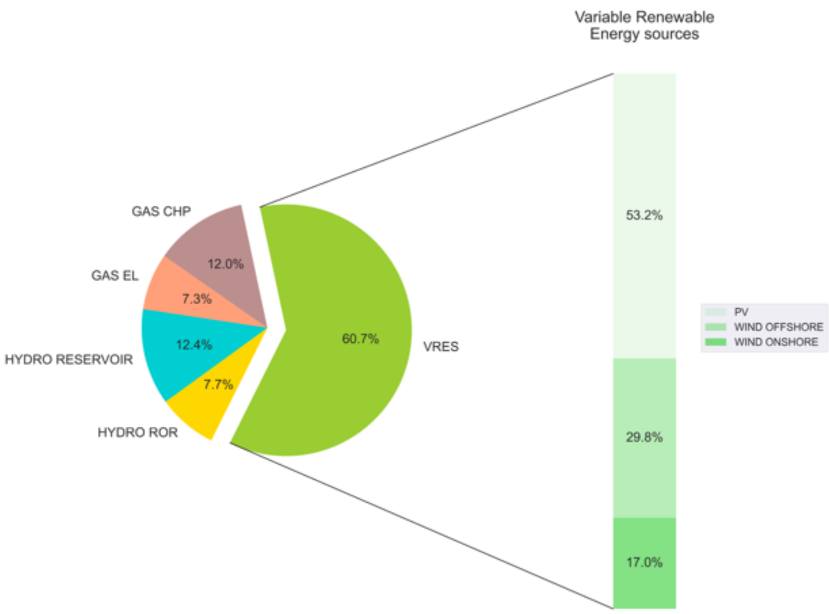

Figure 5.38: Electricity production by 2050 for BH scenario.

5.3 NPC-CO_2 Pareto curve

It is developed a NPC-CO_2 Pareto curve for the *soft* case BH scenario in order to better highlight the role of the hydrogen storage facility. In particular, starting from the value of emitted CO_2 in 2050, which is equal to 20.13 MtonCO_2, it is imposed a lower amount of admissible CO_2 up to the most extreme case where no CO_2 can be emitted by 2050, as summarized in table 5.2.

Table 5.2: CO_2 constraints and technology capacity installed by 2050.

CO2	VRES	ELY	FC	BATTERY
Mton	**GW**	**GW**	**GW**	**GW**
20.1	269.2	13.2	3.4	89.5
10.1	286.0	38.5	9.8	94.5
5.0	298.2	60.7	15.5	84.3
0	312.0	86.3	22.0	81.1

As shown in figure 5.39, the lower the admissible CO_2 limit, the higher the NPC. Indeed, the model is forced to avoid technologies which emit CO_2, such as the gas-base power plant, paid by a higher objective function.

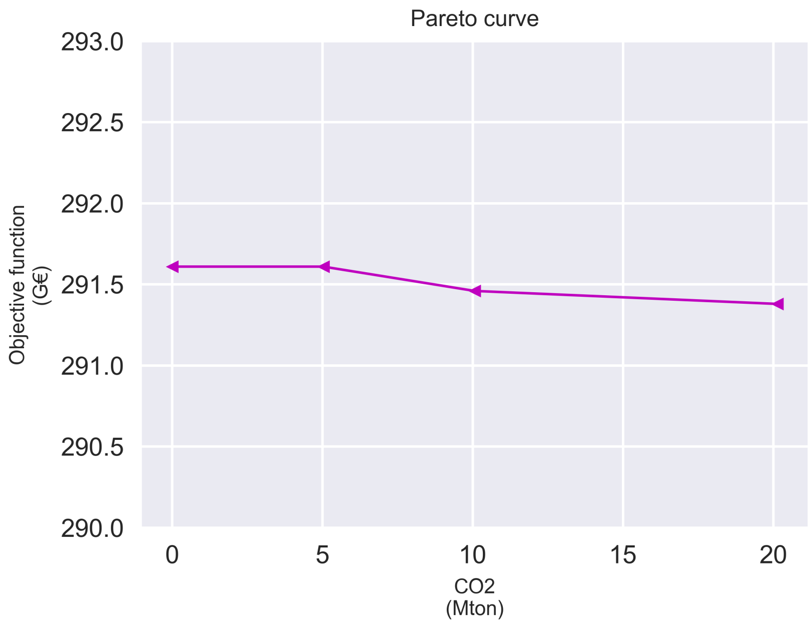

Figure 5.39: NPC-CO_2 emission Pareto curve.

Besides, increasing the CO_2 constraint, a higher share of VRES is installed, based on photovoltaic and onshore wind systems, which capacity increase from 269.2 GW to 312.0 GW by 2050, and therefore a higher capacity of storage is necessary. Nevertheless, it is possible to appreciate that after the fist CO_2 limitation, the amount of battery power component installed starts decreasing to 81.1 GW, while elctrolyzer and fuel cell technologies increase up to 86.3 and 22.0 GW respectively (figure 5.40).

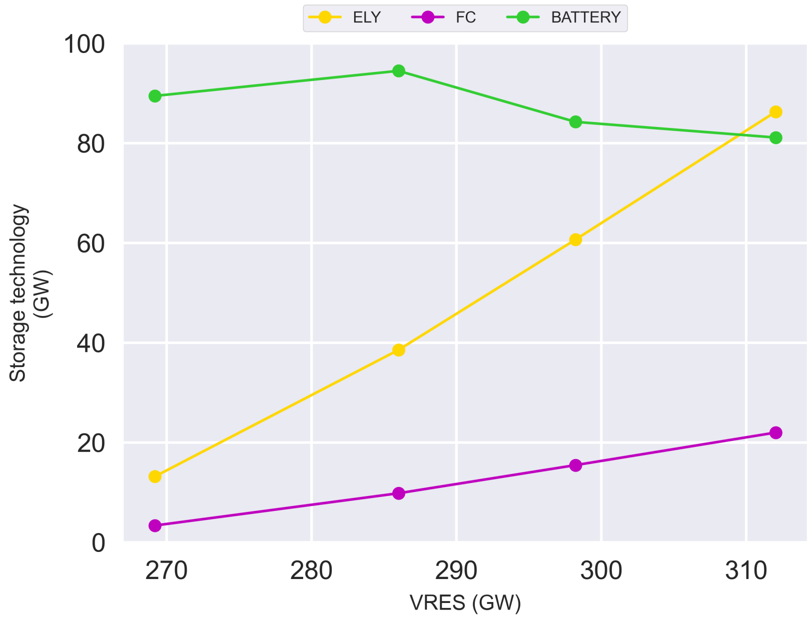

Figure 5.40: Storage capacity evolution in power term with respect to VRES.

In figure 5.41, the storage capacities in energy terms are represented, in particular hydrogen tank and battery storage size evolution. The importance of high-size hydrogen tank is shown as facility for low-carbon scenarios.

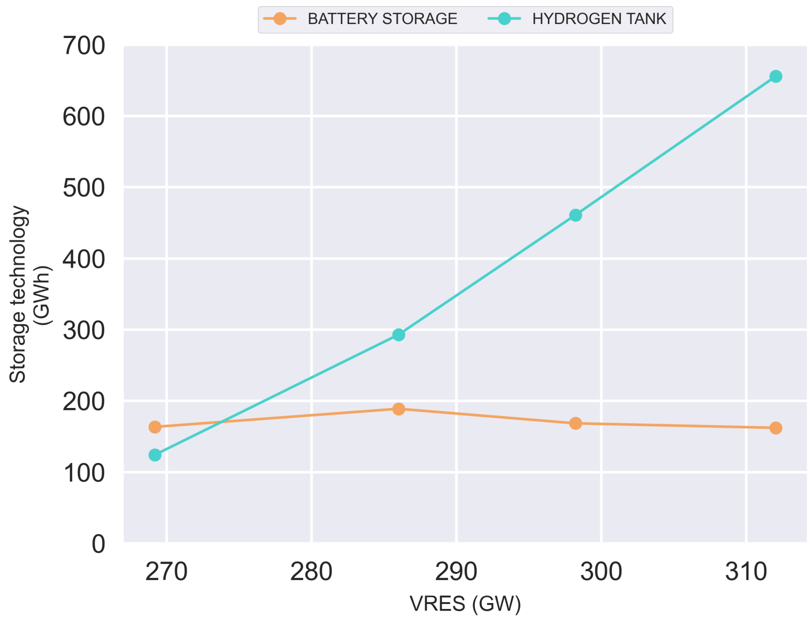

Figure 5.41: Storage capacity evolution in energy term with respect to VRES.

As a result, the energy mix in electricity generation changes from 89.5% RES and 10.5% gas-based plants (figure 5.42), to a 100% renewable system based 19.9% on hydropower and 89.1% on onshore wind and PV (figure 5.43). Furthermore, this analysis highlights the role of hydrogen storage, which is becoming more competitive and thus more important compared to battery storage, which is characterised by higher efficiency and lower costs in the case of high VRES capacity, thanks to low-cost high-capacity hydrogen tanks.

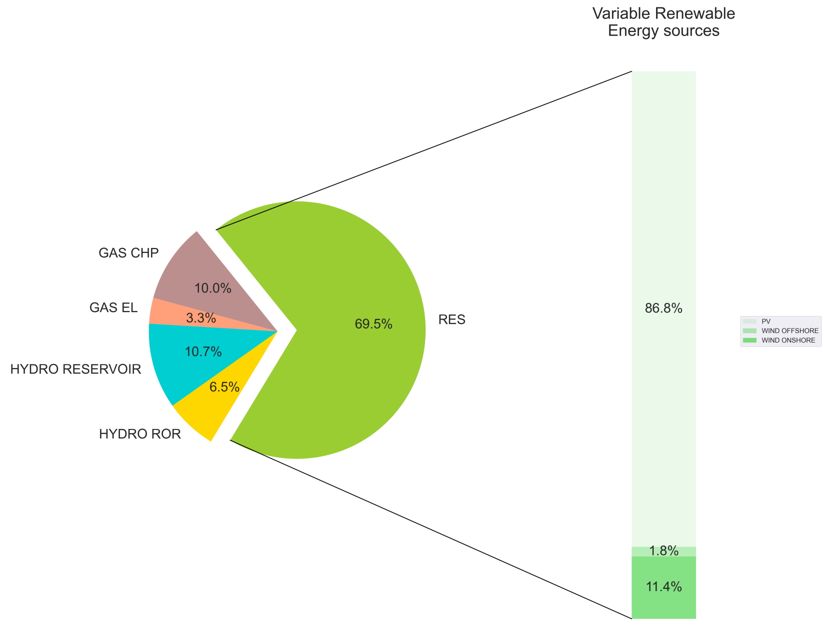

Figure 5.42: Electricity production BH scenario by 2050.

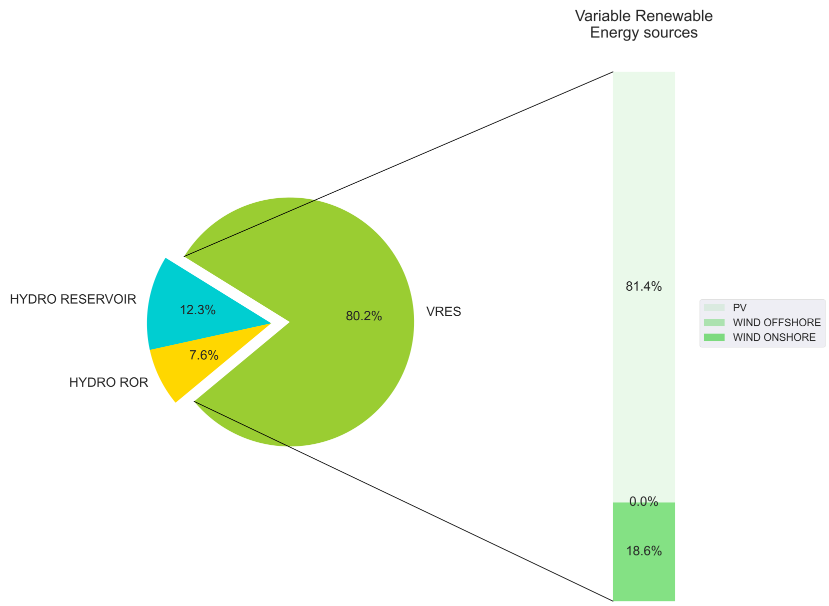

Figure 5.43: Electricity production with 0 CO_2 by 2050.

Chapter 6

Conclusions and future work

6.1 Key outcomes

The aim of this work is to elaborate an energy model for the Italian energy system by carrying out a long-term planning of energy development. The role of VRES is studied, coupling them with different storage technologies. In particular, Li-ion batteries and hydrogen storage are the new energy storage technologies introduced to avoid the oversizing of renewable power plants and to allow a higher flexibility of the power system itself. Therefore, a long-term analysis is carried out using OSeMOSYS (Open-Source energy Modelling System) at the Italian national level, considering a model period from 2021 to 2050.

For this study, an extended version of OSeMOSYS is implemented, applying a specific approach for the time series representation, namely the cluster method. In this way, representative days (RDs) are defined for the different years considering specific attributes: the time series of capacity factors for solar and onshore wind are used for the supply side, while the time series of electricity demand is considered for the demand side. As the number of RDs increases, the computational cost increases. Looking at the convergence of the different parameters, it can be seen that they tend to a stable value as the number of RDs increases, although the difference between 6 RDs and 144 RDs is limited. Therefore, although a higher number of RDs ensures a higher accuracy in the parameter calculation, long-term scenarios are elaborated with 6 RDs.

First, the potential assessment of photovoltaic and wind onshore resources will be developed to determine their technical availability using GIS (Geographic Information Systems). Once the technical potentials are estimated, a comparison is made with a UK onshore wind potential assessment to also consider economic and social parameters that affect the feasibility of installing renewable energy systems. Therefore, two cases are calculated considering both strict and soft constraints: for the *extreme* case, the potential is 26.5 GW and 126.5 GW for onshore wind and solar PV, respectively, while for the *soft* case, the potential is estimated at 86.2 GW and 411.2 GW, respectively. Offshore wind potential is assumed to be 5.5 GW by 2030 and 95 GW thereafter by 2050 by the National Wind Energy Association (ANEV).

Once the number of RDs is chosen and the potential for VRES (*soft* case) is estimated, three main scenarios are developed until 2050, varying the storage technology: Battery-only (OB), Hydrogen-only (OH) and a Hybrid Battery-Hydrogen scenario (BH). In the different cases, a strong increase in VRES can be seen, especially for onshore wind and photovoltaic systems, combined with the installation of storage. Li-ion batteries and hydrogen storage avoid oversizing of renewable systems and allow higher flexibility of the power system itself, leading to a high VRES share in the energy mix. Thank you to the high penetration of renewables, a high share of VRES in the final electricity generation mix is achieved by 2050, which is 69.5% in the OB case, 65.8% in the OH case and 70.6% in the BH case. Furthermore, the most cost-effective energy system is achieved by combining the renewable energy systems with the storage systems in the battery-hydrogen scenario, with a net cost of €291.38 million. However, the most proposed storage technology is the battery due to its higher efficiency and lower cost compared to hydrogen storage, which can only be competitive with a high share of renewables.

Then, a compared analysis is performed with the same three different scenarios OB, OH and BH, imposing a different potential for onshore wind a photovoltaic systems from the *extreme* case estimation. In this case, due to the lower availability of onshore wind and PV, also offshore wind systems are installed in order to meet the final electricity demand, leading also to higher net present costs. As in the *soft* case, the most cost-effective energy system is obtained with the hybrid scenario with a NPC of 297.2 G€.

Finally, a NPC-CO_2 Pareto curve is developed for the battery-hydrogen scenario in the *soft* case. In particular, the CO_2 annual emission limit in 2050 is increased to an extreme case where no emission is allowed. This type of analysis aims in particular to highlight the key role of hydrogen storage. This is because the higher the CO_2 limitation, the higher the objective function. Moreover, the share of installed VRES also increases, leading to an increase in storage facilities. In particular, VRES capacity increases from 269.2 GW without CO2 limitation to 312.0 GW if no CO_2 emission is allowed by 2050. In addition, electrolyser and fuel cell capacities increase from 13.2 GW and 3.4 GW, respectively, to 86.3 GW and 22.0 GW, respectively, if no CO_2 emission is allowed by 2050. As a result, the energy mix in electricity generation changes from 89.5% RES and 10.5% gas-based plants to a 100% renewable system based 19.9% on hydropower and 89.1% on onshore wind and PV. Furthermore, this analysis highlights the role of hydrogen storage, which is becoming more competitive and thus more important compared to battery storage, which is characterised by higher efficiency and lower costs in the case of high VRES capacity, thanks to low-cost high-capacity hydrogen tanks.

Therefore, the analysis carried out shows the possibility and feasibility of a high penetration of renewable energy in energy systems to meet future energy and climate challenges. In particular, wind and solar energy can be used in Italy and contribute to the transition from traditional fossil fuels to a high share of VRES. Nevertheless, storage options must also be considered to avoid both oversizing and a non-flexible energy system. Battery and hydrogen storage can play an important role and lead to a 110% renewable energy system.

6.2 Outlook

Some improvements can be made to this work to better elaborate on some aspects and overcome the limitations. Firstly, this case study assumes a time series for the capacity factor of onshore and offshore wind and solar plants, calculated considering the current state of the art. However, this is a pessimistic approximation that could be improved by considering time series of capacity factors estimated in line with ongoing technological improvement: This could lead to a more consistent prediction of power systems and highlight the contribution of VRES.

Moreover, the analysis of the energy system could be extended to sectors other than electricity generation, such as heat and transport. In this way, the Italian energy system could be modelled with a more comprehensive view, since the actual interaction between these sectors is not taken into account in this case study.

The electricity grid study is also another important point. Indeed, further analysis should be performed in order to examine how the VRES increase in the final energy mix affects the electricity network in term of stability.

Finally, further studies could be carried out to assess the interactions of energy transfer between border countries, which could provide a more cost-effective solution for the Italian energy system.

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