– **Deliverable D1.1** –

Definition and specification of Dynamic Virtual Power Plant (DVPP) scenarios

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Executive summary

In this deliverable, different possible scenarios that can be used for the analysis of realistic Dynamic Virtual Power Plants in Europe have been presented and discussed. The main blocks of the present document can be summarized in the following:

- First, the context and background are introduced, emphasizing on the following: the European policies that are planned for 2030 and 2050, in terms of emissions reduction to meet the global environmental goals; the classic concept of Virtual Power Plant, as compared to the concept of Dynamic Virtual Power Plant; a review of the most relevant generation technologies, summarizing and quantifying the technical aspects that are relevant for their operation in the context Dynamic Virtual Power Plants; and a general study of the availability of renewable resources in Europe, focusing on wind, solar and hydro.
- Next, different types of scenarios are considered, with the objective of obtaining a range of options in terms of size, renewable generation technologies, and electrical network configuration. On one hand, a set of scenarios considering these aspects is generated from a conceptual point of view. On the other hand, a review of the existing electrical grid in several European countries has been conducted, in order to identify real scenarios in specific locations that are potentially suitable to allow for the operation of Dynamic Virtual Power Plants, serving as reference for the selection of a final set of scenarios, considering isolated (e.g., island) and interconnected (e.g., continental) cases.
- Finally, the scenarios selected are quantified through an optimization-based algorithm. In order to do so, specific locations in Europe are selected, and real data related to the availability of different renewable resources, as well as the demand, has been used. This does not intend to be a detailed study on energy systems planning and specific electrical network layout, as that would require a large amount of highly accurate data and forecasting studies, taking several variables into account. Instead, a less complex methodology using available data is proposed to serve as a first approximation of the renewable plants sizing, considering present and future scenarios, aiming at meeting specific requirements of grid integration of renewables. The proposed scenarios also are intended to be used as a basis for further studies within other work packages of the Posytyf project, as well as other related works.

Therefore, the fundamental aspects of Dynamic Virtual Power Plants have been addressed in this first deliverable, from very conceptual to more practical and technical points of view. The specific renewable generation units' portfolio of the Dynamic Virtual Power Plant will depend on the specific location and the potential resources that are available in the area. Bearing that in mind, it must be ensured that the different generation technologies that are present in the grid operation area are able to fulfil the energy needs at every instant of time and in the worst-case scenarios of resource availability, meaning that some of these technologies, such as solar thermal and hydro, will play a key role in the system.

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1 Background and definitions

1.1 European environmental policies

European environmental policies are aimed at retaining and reinforcing the world leadership of the EU in renewable energies (RE). This is not only seen as a matter of security of supply and climate change policy, but also as an industrial policy imperative to fully exploit the green growth potential [1].

The original Renewable Energy Directive (2009/28/EC) [2] established an overall policy for the production and promotion of energy from renewable sources in the EU. It required the EU to fulfil at least 20% of its total energy needs with renewable energy by 2020, to be achieved through the attainment of individual national targets. By 2018 the EU realized an 18% share of energy from renewable energy sources (RES) with twelve member states meeting their 2020 targets early.

1.1.1 Horizon 2030

In December 2018, the recast Renewable Energy Directive 2018/2001/EU [3] entered into force, as part of the Clean energy for all Europeans package [4]. This directive sets a new binding renewable energy target for the EU for 2030 of at least 32%, with a clause for a possible upwards revision by 2023, but it does not specify binding national targets. It comprises measures for the different sectors to ensure that the EU's target is achieved cost-effectively, among them:

- Allocation of funds on the reduction of the capital cost of RE projects.
- Development of essential infrastructures such as transmission and distribution grid infrastructure, intelligent networks and interconnections.
- Promotion of best practices between the competent authorities or bodies to enable a higher uptake of cost-efficient renewable energy projects.
- Encouragement of investments in new, flexible and clean technologies.
- An adequate strategy to manage the retirement of technologies which do not contribute to the reduction of emissions or deliver sufficient flexibility.
- Definition and protection of support schemes to foster the market integration and deployment of renewable electricity.
- Simplification of administrative permit granting processes, and clear time-limits for issuing the authorization of electricity generation installations.

The recast Renewable Energy Directive 2018/2001 also includes some new instruments to facilitate renewable energy cooperation in addition to the mechanisms already set out in the 2009 RES Directive. Specifically, Article 5 of the Directive establishes that Member States shall have the right to decide to which extent they support electricity from RES which is produced in another Member State, but also encourages Member States to open participation in support schemes for electricity from RES; as indicative figures a share of at least 5% from 2023 to 2026 and at least 10% from 2027 to 2030 are specified. In addition, Article 8 of the Directive establishes that statistical transfer of energy generated through RES from one Member State to another would be managed through a Union renewable development platform ("URDP"), which the Commission shall establish. The URDP will be able to match the demand for and supply of the amounts of energy through RES and will also have the role to reduce administrative issues for RES cooperation.

Under the Regulation on the Governance of the Energy Union and Climate Action (EU) 2018/1999 [5], the EU countries submitted their National Energy and Climate Plans (NECPs) for 2021-2030, outlining how they will meet the 2030 targets for renewable energy and for energy efficiency. On September 17th, 2020, the EC published the Final NECPs received up to date [6]. The overall assessment of the NECPs [7] shows that for renewable energy, the combined commitment by EU countries is estimated at 33.1-33.7%, concluding that the EU is on track to surpass its current 2030 greenhouse gas emissions reduction target of 40%.

Figure 1 gathers the targets of RES share in % of gross final energy consumption for the EU-27 in 2020 and 2030, together with the expected share in 2030 for final electricity consumption (RES-E) of each country, according to their NECP commitments.

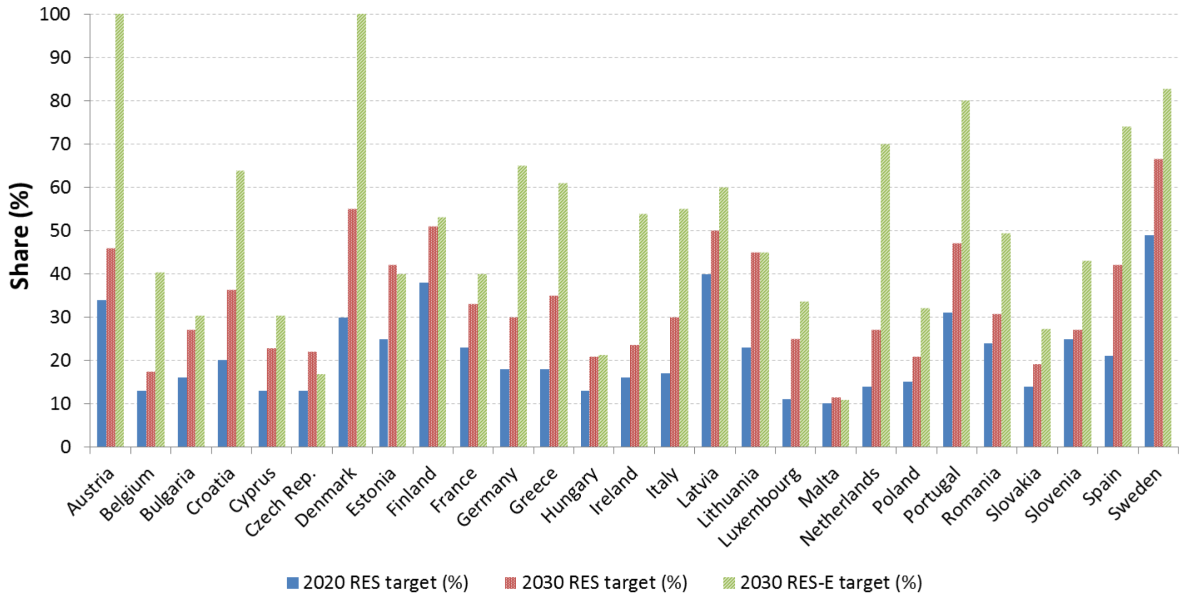


Figure 1. Targets of RES share in % of gross final energy consumption for EU countries in 2020 and 2030 and RES share for final electricity consumption (RES-E) in 2030 (source: NECPs [6])

Some examples of energy mix proposals from different countries, according to their NECPs, are detailed next:

- **France** defines a target of 40% for the share of RES in final electricity consumption (RES-E) by 2030. To achieve this percentage the contribution of the following RES would increase as follows: a) hydropower from 25.3 GW in 2016 to 26.7 GW (Scenario B) in 2028; b) onshore wind from 11.7 GW in 2016 to 34.7 GW (Scenario B) in 2028; c) solar PV from 7 GW in 2016 to 35.1-44.0 GW in 2028; d) offshore wind and renewable marine energies would appear with 5.2 to 6.2

GW in 2028. The French NECP does not include the contribution of CSP plants in their national energy mix.

- **Germany** defines a target of 65% for the share of RES in final electricity consumption (RES-E) by 2030, which is probably one of the most ambitious plans in all Europe. To achieve this percentage the indicative targets of installed capacity of RES are: a) onshore wind would have about 67-71 GW; b) solar PV would have about 98 GW; c) offshore wind would have 20 GW; d) biomass would contribute with 8.4 GW; and finally, e) hydropower and others would contribute with 6 GW of installed capacity.
- **Spain** has established a target of 42% of RES share on energy end use. The Spanish PNIEC [8] presents also indicative targets of installed capacity of RES by 2030. In particular the share of CSP installed capacity would increase from 2,300 MW installed in 2015 to 7,303 MW in 2030, while the installed capacity for PV would increase from 4,854 MW in 2015 to 39,181 MW in 2030. Wind installed capacity, which currently contributes in a significant amount to the electricity grid in Spain, would increase from 22,925 in 2015 to 50,333 MW in 2030. The ratio of installed capacity expected for Wind/PV/CSP is still under discussion in Spain, since several stakeholders (for example Protermosolar [9]) suggested to reconsider these percentage of RES to guarantee the electricity supply on 24 hours basis (focusing on the role of energy storage) and maintaining at the same time reduced energy prices (combined cost of Wind/PV/CSP < 5 c€/kWh).

Figure 2 displays the technology breakdown of current installed RES capacities (in 2019) for relevant EU countries and the corresponding values expected by 2030 for each country according to the NECPs, arranged in decreasing order. Only the EU countries that pledge a total RES capacity higher than 5 GW by 2030 are included.

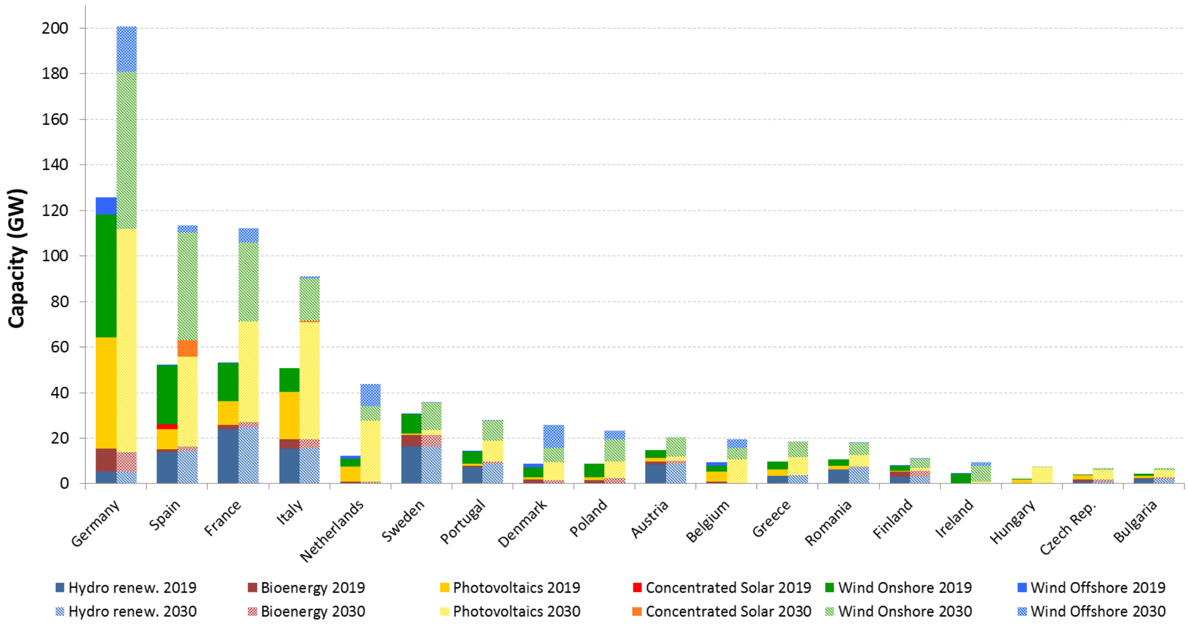


Figure 2. Technology breakdown of RES capacities for relevant EU countries in 2019 and 2030 (source: IRENA [10] and NECPs [6])

Globally, the NECPs pledge around 210 GW of additional solar PV capacity by 2030, meaning 19 GW per year and positioning solar PV as the most installed energy technology in the 2020-2030 decade. Wind energy is expected to be the second highest contribution to the European RES capacity by 2030, representing more than 150 GW of new wind power capacity (around 100 GW onshore and 50 GW offshore).

Regarding concentrating solar power (CSP), small overall additions are expected by 2030, mainly in Spain (5 GW) and Italy (880 MW). Nevertheless, since the total CSP capacity currently existent in Europe is still low, this will represent a 150% increase in its installed capacity. Finally, bioenergy (biomass, biogas…) for electricity production and renewable hydroelectric power are not expected to increase significantly, according to the NECPs.

In order to outline a geographical overview of RES for the electricity sector in 2030, Figure 3 represents in the EU countries map the RES shares for final electricity consumption (RES-E) (in different intensities of green color), and the relative breakdown by technologies (in pie charts for each country) expected for 2030.

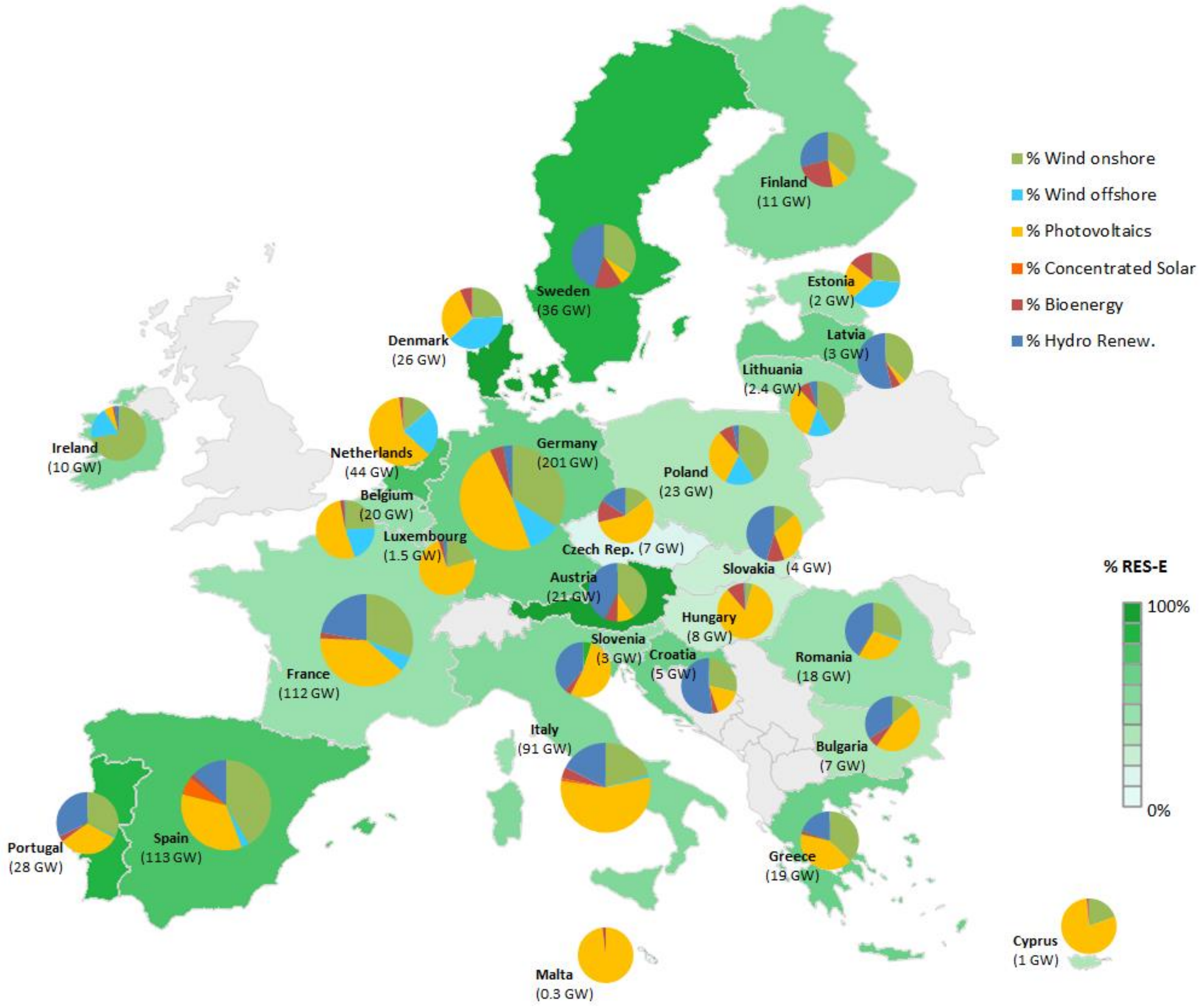


Figure 3. Targets of RES-E share in EU countries for 2030 and technology breakdown of RES capacities expected in 2030 for each country (source: elaborated from NECPs [6])

1.1.2 Horizon 2050

The EU is committed to reducing greenhouse gas emissions to 80–95% below 1990 levels by 2050 [10]. To that end, electricity will have to play a much greater role than now, increasing significantly its share in final energy demand (from 22% in 2017 [11] to 36–39% in 2050 [12]). In this context, electricity production needs to be almost emission-free. This implies that about two thirds of the EU energy should come from renewable sources.

The specific share of RES deployment depends on the environmental policies adopted by the EU. Nonetheless, the RES share should rise substantially in all the scenarios foreseen in the EU roadmap [12], achieving at least 55% in gross final energy consumption by 2050. For instance, a scenario with high energy efficiency measures, involving a decrease in energy demand of 41% by 2050 compared to 2005, would provide 60–65% of electricity consumption from RES. On the other hand, a high renewables scenario with strong support measures for RES would lead to a very high share of RES in gross final energy consumption (around 75% in 2050) and a share of RES-E reaching 97%. This scenario must include significant electricity storage to accommodate varying RES supply even at times of low demand. A recent prospect by IRENA [11] proposes RES and RES-E shares of 70% and 86%, respectively, as a reasonable energy transformation scenario to accomplish the EU emission targets.

In the near future, wind energy from the northern seas and the Atlantic sea basin (in countries like Germany, Denmark, Sweden, France and the Netherlands) can supply substantial quantities of electricity with declining costs. By 2050, wind power could represent more than 620 GW [11] of installed capacity in the EU with strong support measures.

Besides, solar power could represent a great opportunity for the Mediterranean countries (such as Spain, Portugal, Italy and Greece) where large-scale solar projects can be developed. According to recent prospects [11] [13], around 800 GW of PV capacity could be installed in order to achieve a renewable-based energy system by 2050. In addition, CSP technology could take advantage of its energy storage capabilities, providing a dispatchable and stable capacity in the range from 26 to 100 GW [14].

The overall hydroelectric power capacity of the UE (around 120 GW of renewable hydropower, not including mixed plants with fossil fuel support) is not expected to change significantly. On the other hand, the capacity of bioenergy plants for electricity production could be increased from the current 34 GW in 2019 to around 107 GW by 2050 [11] in order to reach the foreseen goals of RES share.

1.2 Virtual Power Plant concepts

1.2.1 "Classic" Virtual Power Plant

Virtual Power Plant (VPP), as a concept, dates back to 1997, when Awerbuch and Preston proposed the idea of Virtual Utility [15]. They defined the Virtual Utility as a "flexible collaboration of independent, market-driven entities that provide efficient energy service demanded by consumers without necessarily owning the corresponding assets". From this definition, the key word is ***flexibility***, implying the integration of any type of energy resources, including renewable and non-renewable generation units, flexible demands, and energy storage systems, among others. The initial concept of VPP germinated from the need of tackling the relatively low competitiveness of the back then emerging non-dispatchable renewable energy sources, such as wind and solar generation, when compared with large, dispatchable conventional generation, such as hydro and thermal power plants. To increase this competitiveness is clearly essential to pave the way to an eventual mass integration of such renewable sources.

The concept of VPP has naturally brought (and still does) an enormous interest during the last two decades, and a huge number of new assets, applications, scenarios and business cases have been studied, tested, and to some extent, implemented in practice. However, the main idea behind the VPP concept remains the same, i.e., to combine a number of independent assets in order to provide a flexible and economic solution to utilities that otherwise could not. In this regard, it is convenient to make a distinction between the concept of VPP that will be studied in POSYTYF, and other solutions that, although showing conceptual similarities with the VPP, possess important differences at the structural and operational levels, namely the Microgrid (MG), the Active Distribution Network (ADN), and the Load Aggregator (LA) [16]. The main differences between VPP, MG, ADN and LA are summarized below.

1.2.1.1 Virtual Power Plant

By integrating a number of diverse distributed energy resources (DERs) into a VPP, such DERs are placed in a stronger position to participate in the electricity markets, which can even lead to a transition from a price-taker scenario to a price-maker one. Such markets include the day-ahead (DAM), real-time (RTM), ancillary service (ASM) and futures (FM) markets. VPPs allow DERs to achieve more profits from the aforementioned markets, thus improving their competitiveness against conventional market participants. Moreover, VPPs allow the integration of DERs which need not be installed in the same geographical region, which greatly increases the possibilities of such VPPs, even enabling their participation in grid-scale markets. Their flexibility in the market participation is also a relevant feature of VPPs. For instance, if part of its generation and flexible demand are located within a specific region, VPP can choose to feed its local load (controllable or not), thus avoiding buying electricity from the main grid. In the same scenario, the VPP can alternatively seek to maximize its profit buying/selling energy from the main grid according to available forecasts of the wholesale electricity price and stochastic renewable source variations.

1.2.1.2 Microgrid

According to [17], an MG is a "group of interconnected loads and DERs with ***defined electrical boundaries*** forming a ***local*** electric power system at ***distribution voltage levels***, that acts as a single controllable entity and is able to operate in either grid-connected or ***island mode***". The terms highlighted in bold in the definition above indicate the main differences of an MG with respect to a VPP, i.e., an MG is (i) geographically delimited (a VPP may not be restricted in this regard), (ii) local in the sense of interaction with the main synchronous grid (a VPP can either be local or system-wide), (iii) connected at distribution voltage levels (a VPP can be composed of assets connected at either transmission or distribution levels), and (iv) capable of operating in island mode, i.e., isolated from the main grid (a VPP is not). Note that a VPP can be a subset of an isolated system (e.g., an island), meaning that some elements of this island are not part of the VPP. If all the elements are part of the VPP, that would result in the particular case of a microgrid. From the main objective point of view, while the VPP generally aims at enhancing the competitiveness of the resources that are integrated by maximizing its profit, the operation target of the MG is to ensure the stable, reliable and resilient operation of the resources within the MG, and when grid-connected, to participate mainly in RTMs such as the balancing service market and/or ancillary services market and to minimize the costs of the power purchased from the main grid. Note that, given the relatively small size of the MG with respect to the main grid and its constrained network topology, its participation in the DAM is not as competitive as for the VPP.

1.2.1.3 Active Distribution Network

The concept of ADN is similar to that of MG discussed above. The main difference lies in the fact that an ADN is not capable of operating in island mode. Aside of this difference, the ADN, as in the case of an MG, relies on a bidirectional power exchange with the main grid with the aim of enhancing the reliability and utilization of the resources within the distribution network. While participation in the DAM is limited due to the local and geographically constrained nature of the ADN, it can participate in RTMs such as the balancing and ancillary services markets.

1.2.1.4 Load Aggregator

An LA consists in the coordination of a group of loads, both conventional and flexible, to effectively and reliably manage its aggregated demand. Evidently, electricity generation is not considered in LAs. Although mainly participating in the RTMs, LAs can also participate, if large enough, in the DAM as they can provide peak shaving and load shifting

From the classification above, it is clear that the main feature that characterizes VPPs is the fact that they are not geographically constrained, i.e., the assets comprising the VPP need not be geographically nor electrically close to each other. This indeed provides VPPs with a remarkable advantage from both technical and economic points of view with respect to the other solutions listed above. Moreover, this feature allows the integration of any controllable resource into the VPP, including dispatchable generation (both renewable and non-renewable); non-dispatchable, stochastic renewable generation; flexible demands; and energy storage devices. Note that such resources could also be owned by different utility companies. In this regard, within POSYTYF the focus is on VPP-based solutions where only renewable generation (both dispatchable and non-dispatchable) and flexible demands are present. Additionally, non-electrochemical energy storage systems, i.e., systems that are not based on the mainstream batteries (e.g., flywheels, ultracapacitors, etc.), are considered given their increasing presence, and which is expected to continue in the upcoming years. The main goal of the project is thus to provide RESs and flexible demand owners with knowledge, models and tools that will increase the flexibility, and consequently, the competitiveness of such assets against conventional, non-renewable generation.

1.2.2 Dynamic Virtual Power Plant

1.2.2.1 Structure

Components: A DVPP is a set of Renewable Energy Sources (RES) grouped together by mainly commercial purposes (association of several geographically distributed generators owned/run by the same company/entity) and with the objective to ensure ancillary services.

The following dynamic devices will be considered as possible components of the studied DVPP:

- Photovoltaic generators
- Solar thermal generators
- Wind generators
- Hydro generators
- Biomass generators
- Hydrogen generation (in the distribution part)
- Synchronous condensers (in the transmission part)
- Flywheels (in the transmission part)
- Flexible demand (dispatchable loads)

The following devices will not be considered in this project as components of DVPP:

- Electrochemical storage
- Classic thermal generators

Perimeter: One DVPP may include dynamic devices from both transmission and distribution grid levels (black and gray lines, respectively, in Figure 4). Thus, components of a DVPP are not necessarily neighbors. Moreover, some neighbor generators may not participate to the DVPP (devices not included in neither DVPP 1 nor DVPP 2, see External power system (legend) in Figure 4). They should be considered as disturbances/dynamic interactions in synthesis of the DVPP controls.

Also, several DVPP (1 and 2 in Figure 4) can be considered. Thus, neighbor generators may belong to different DVPP.

The perimeter of a DVPP will be considered fixed in a first approach. As an option, time-variable perimeters can be investigated in a second stage.

Data availability: for controls, availability of measures is capital. This is important, especially for second level controls (to ensure ancillary services) and for coordination of control actions in general (as DVPP actuators are geographically distant). It is supposed that voltage and frequency measurements from both transmission and distribution sides will be available at a common control point called DVPP dispatching in the sequel. Controls will be computed in the DVPP dispatching and sent back to the DVPP actuators. The above-mentioned measures can be classic or PMU.

1.2.2.2 Ancillary services: voltage

The DVPP should provide voltage support as the classic generation. This means to fulfill same kind of objectives and to be able to participate in the same kind of regulation schemes.

The current objectives are:

At transmission level:

- Regulate voltage at connection points of generators
- Manage reactive power reserve of each generator (Q regulation/alignment)
- Regulate voltage at some strategic points of the grid – pilot points

At distribution level:

- Maintain terminal voltage between limits Vmax/min
- Manage reactive power exchange at the connection point with the transmission grid

As an option, damping of grid oscillations (inter-area or coupling modes) can be considered. The current framework considers local regulation and participation to the secondary voltage control level. An important point is to manage in a coordinated manner the DVPP RES generators which belong to the transmission and distribution grid sides.

1.2.2.3 Ancillary services: frequency

DVPP generators should participate to primary and secondary frequency control levels.

Equilibrium at 50 Hz is mandatory for Scenario A (DVPP in actual context of the power systems and regulatory items). Relaxation/evolution of this principle will be discussed for Scenario B (systems with high RES penetration and low inertia).

Grid forming is a priori intended for primary regulation and grid following for secondary one. A study for this will be done in WP1.

An example of a grid operation area containing two DVPPs is shown in Figure 4.

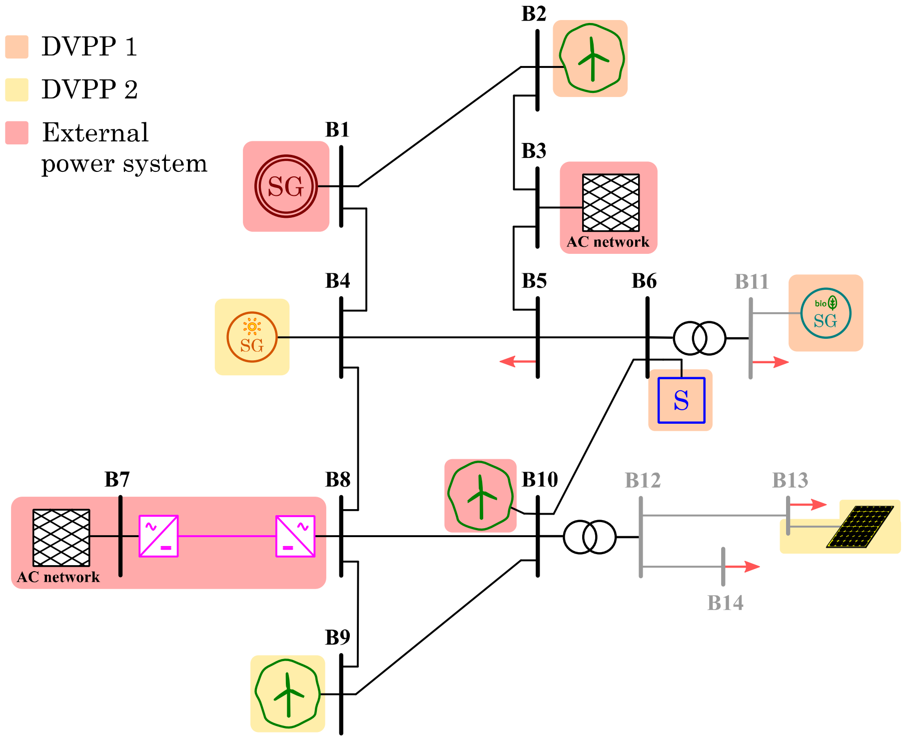


Figure 4. Grid operation area containing two DVPPs

1.3 Technologies

1.3.1 Introduction

The following Subsection describes the main generation technologies that could be part of a DVPP:

- Solar energy
    - Photovoltaic
    - Solar thermal
- Wind energy
    - Onshore wind energy
    - Offshore wind energy
- Hydropower
- Biomass
- Geothermal
- Non-electrochemical storage
    - Pumped-storage hydropower

Note that thermal power (e.g., coal-fired, combined cycle or nuclear) can be inside the grid operation area, but are not part of the DVPP.

Besides, their most relevant features and characteristics of each of them are described, focusing on the following:

- Response time
- Controllability
- Dispatchability
- Inherent storage time
- CO2 emissions
- Costs associated to each electricity generation technology:
    - LCOE
    - CAPEX
    - OPEX
    - Energy cost

1.3.2 Electricity generation technologies

1.3.2.1 Solar energy

Solar energy technologies use solar radiation as a resource to generate electricity. Average solar irradiance outside the atmosphere is approximately 1.35 kW/m^2. However, due to attenuation caused by the atmosphere, it drops down to a 24 hour annual average of 0.2 kW/m^2 at sea level. Solar irradiance varies regionally, being higher in places close to the equator and lower at higher latitudes, and with different time scales: seasonally, hourly, and each minute or second. Furthermore, passing weather conditions have a huge impact on instant power generation since they can cause relatively fast variations in intensity [18].

There are two main solar based technologies: solar photovoltaic (PV) and solar thermal. The former uses semiconductor devices known as photovoltaic cells for the direct conversion of solar energy into electricity. The latter utilizes thermal energy as an intermediate conversion to feed a thermodynamic cycle (mainly Rankine steam cycle) to drive a turbo generator. Both technologies are expected to contribute broadly to the near future renewable energy share, especially PV systems, as a result of its potential of cost reduction as seen during the past years. Next, some of the most relevant features of each solar energy technology are addressed.

Solar photovoltaic

Photovoltaic systems encompass several PV modules (Figure 5). As previously stated, the level of incident radiation (direct or diffuse) defines the power output generation. These modules are characterized by the well-known I-V curve, which depends on external conditions, such as solar radiation levels and temperature. In order to obtain the maximum power output, the module must work as near as possible to the maximum power point (MPP) which is close to the knee of the I-V characteristic curve. For this purpose, power electronic devices are constantly tracking the MPP considering solar radiation and temperature variations. Furthermore, these are employed for DC/AC conversion to connect the PV system into the grid.

The quality of the PV cells can be assessed by the squareness of the I-V characteristic by means of the fill factor. Although PV modules have negligible inherent storage capability, this can be provided by external devices. Lastly, solar radiation variability which causes instantaneous changes in power output capacity, can be mitigated via geographically spread interconnected PV systems.

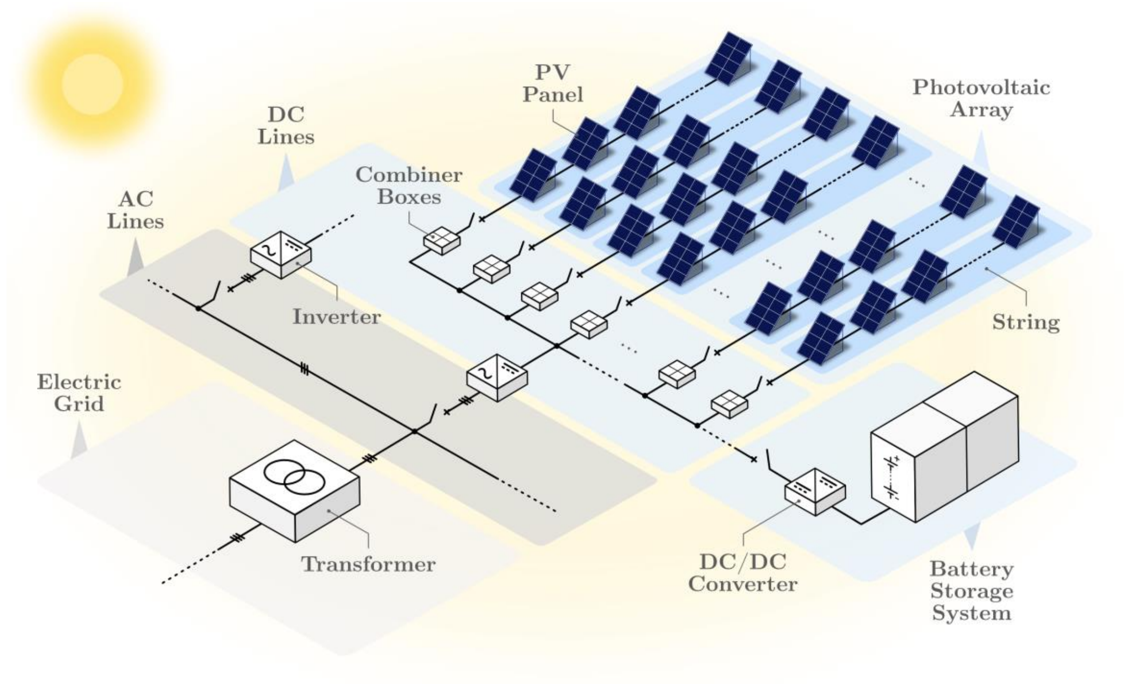


Figure 5. General scheme of a photovoltaic power plant

Solar thermal

Solar thermal technologies use solar concentrators to produce the required high temperatures to raise steam so as to drive heat engines, mainly turbines in the commercial plants. Solar thermal works like the boiler in a conventional thermal power plant with a Rankine cycle. Steam temperature is critical to obtain acceptable conversion efficiencies. Three proven technologies, requiring direct or beam radiation, are appropriate for large scale generation: parabolic troughs and linear Fresnel reflectors (both corresponding to linear focus technology) and solar towers (Figure 6) or dishes (point focus technology).

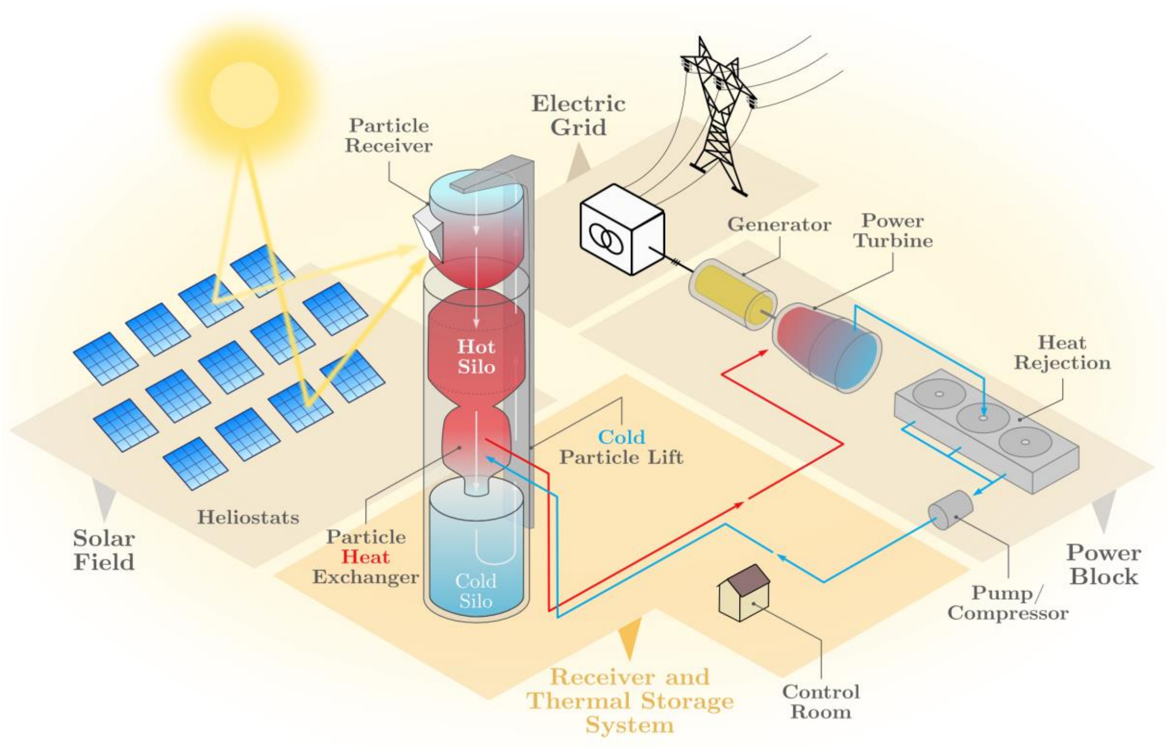


Figure 6. General scheme of a solar thermal power plant (linear focus or tower)

Parabolic-trough collectors and linear Fresnel reflectors, usually arranged in large solar fields, focus solar radiation on to a receiver pipe which contains a heat transfer medium such as thermal oils or pressurized water. Next, the heat transfer medium is collected and introduced into a heat exchanger where steam is raised for supply to the turbines. As a means to increase the operating temperature, and thus overall efficiency, steam can be further heated using conventional fuels. Currently, operation temperatures in commercial systems vary between 350 and 400 °C.

On the other hand, solar power towers comprise a central receiver surrounded by a field of concentrating mirrors or heliostats which track the sun. Sunlight is reflected on heliostats and concentrated on to the receiver (located on top of the tower). There, in a similar manner as the previous technology, solar energy is absorbed by the heat transfer medium (water, molten salts, atmospheric/pressurized air, etc.). In this case, temperatures close to 600 °C can be achieved when molten salts or water/steam are used as heat transfer medium. In the long run, the potential cost reduction of solar power towers is expected to be more noticeable than in parabolic-trough plants.

Since solar thermal technologies involve a thermal intermediate stage, depending on design details, thermal energy storage of large capacity can be implemented (for instance, by means of molten salts). In addition, as both technologies rely on solar irradiation for efficient operation, they can be combined with fossil fuel combustion in order to operate continuously. Consequently, the primary advantage of these hybrid systems is their capability to supply power on demand. Regarding distributed electricity generation, parabolic dishes are a smaller scale alternative to the aforementioned concentrated solar thermal technologies mentioned, but currently they are not competitive with PV.

1.3.2.2 Wind energy

Differential solar heating on earth's atmosphere creates large scale movements of air masses which produce winds. Similar to hydropower generation, wind energy can be considered an indirect form of solar energy. Air flow is established due to the pressure gradient between high pressure and low-pressure zones. This gradient determines the initial speed and direction of wind flow. It is very important to consider the variety of local factors that affect wind flows such as differential land or sea heating, mountains, valleys and buildings.

Since the atmosphere's boundary layer is at approximately 1000 meters, wind availability depends on turbines' hub height. In the context of the European Union, onshore and offshore wind resources have been estimated at 4800 TWh/year and 3000 TWh/year, respectively [18]. Wind power is one of the most developed renewable energy technologies and it is expected to have a significant share in the future energy mix. Furthermore, it has very competitive production costs, similar to those of traditional generation technologies.

One major concern regarding wind energy technologies' investment and commissioning is wind speed variability, in view of the fact that this could have an adverse effect on the grid supply and stability. Different time scales can be considered: annual, seasonal, synoptic, diurnal or turbulence, ranging from year to year to second to second. It can be demonstrated that the largest contribution to variation is the synoptic variation (passing weather systems). Fortunately, these are slow (3 to 5 days) in the context of large power systems' operation. Contrary, turbulence regimes impact on short term operation but its effect can be reduced aggregating several wind farm systems. Lastly, the spectral gap between 10 minutes and two hours (when there is least variation) is the interesting time scale for power system operation. The aforementioned variability could be described using a probability distribution or a spectral density representation. It is worth mentioning that aggregate output from several geographically dispersed wind farms has less longer-term variability than the output from a single wind farm [18]. Two types of wind farms can be distinguished: onshore wind farms (Figure 7) and offshore wind farms (Figure 8). Both types have several subsystems in common such as AC connections between turbines, busbar, transformer, etc. Regarding offshore wind farms, these might require exporting the generated power through HVDC (see Figure 8) when the wind farm is remote (more than 80-100 km, approximately). Lastly, based on its interconnection different grid topologies can be found, e.g. radial, ring or star configurations [19].

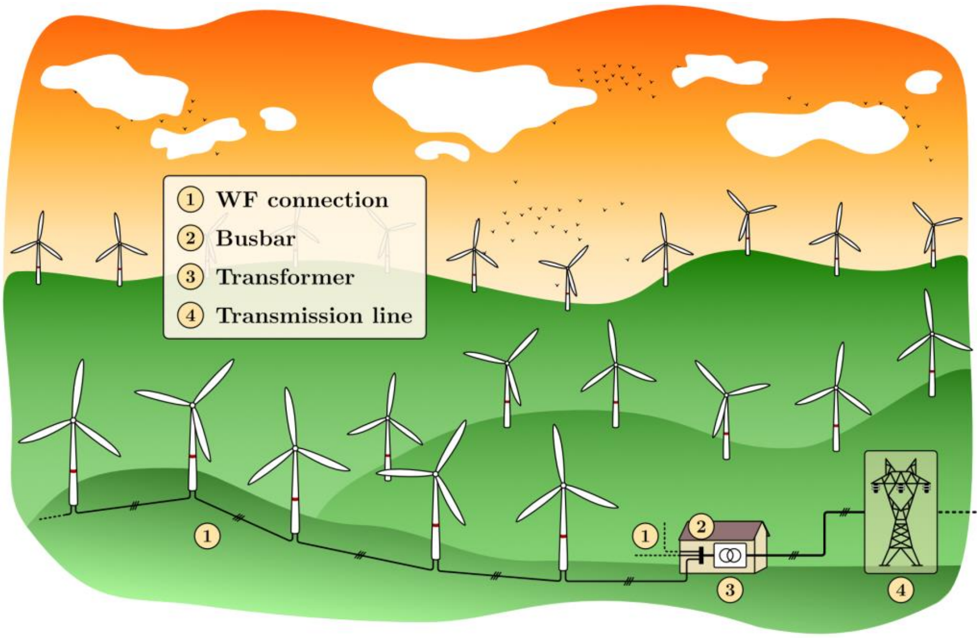


Figure 7. General scheme of an onshore wind farm

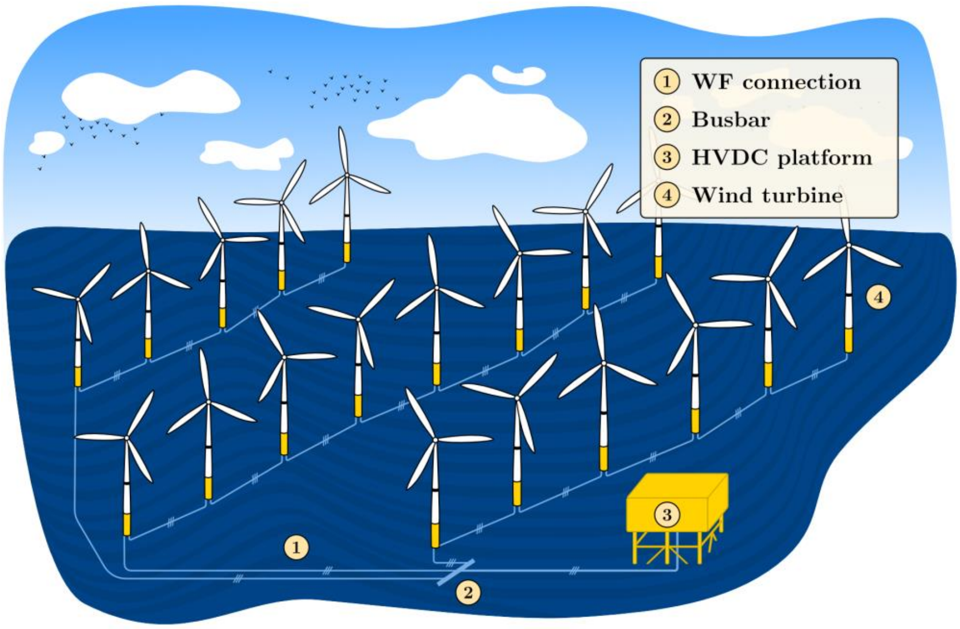


Figure 8. General scheme of an offshore wind farm

The power that a wind turbine can extract from wind is proportional to the cube of the wind speed. Therefore, the variability in power output would exaggerate substantially wind speed variability. Wind turbines are designed to generate its nominal power output within a range of rated wind speeds. The cut-in wind speed determines the minimum wind speed at which a wind turbine is available for operation. On the other hand, if wind speed surpasses an upper threshold named cut-out wind speed, the wind turbine is shut down. Typical capacity factors lie in the range of 0.25-0.45 of the rated output. The upper limit that defines the aerodynamic efficiency of a rotor is known as the Betz limit. In order to operate at maximum power output, the tip-speed ratio (which relates angular velocity of the rotor, the radius and the incident wind speed) must be held constant. This is the reason why most modern wind turbines operate at variable speed. This concept is interesting from an integration perspective since the rotor inertia could be used to smooth short transients or variations in wind speed. An illustration of the different parts of a wind turbine is shown in Figure 9. As it is shown, different components can be identified, from the hub to the wind farm connection.

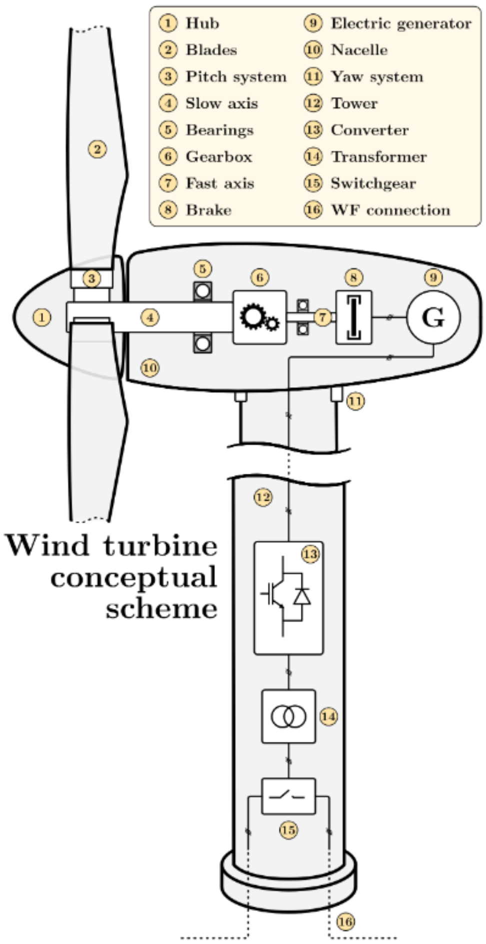


Figure 9. Main components of a wind turbine

Reference [20], enumerates some widely used wind turbine technologies and presents its most relevant features. For instance, control bandwidth or time response is within 0.5 ms to 1 s, depending on the technology (fixed or variable speed). Besides, wind turbines don't have any inherent storage capability.

1.3.2.3 Hydropower energy

Hydroelectric power generation can be considered as an indirect form of solar energy. Evaporated water from the sea or inland areas eventually falls on high ground as a result of rainfalls. Therefore, water has gained potential energy as a consequence of incident solar radiation. Hydropower technologies take advantage of either water's potential energy or its kinetic energy as water flows back towards the sea.

Three main hydropower technologies can be distinguished: large scale hydropower (created by damming rivers), run-of-river hydropower and pumped-storage hydropower plants (PS-HPP) (Figure 10). The suitability of each technology is highly dependent on the local topography [18].

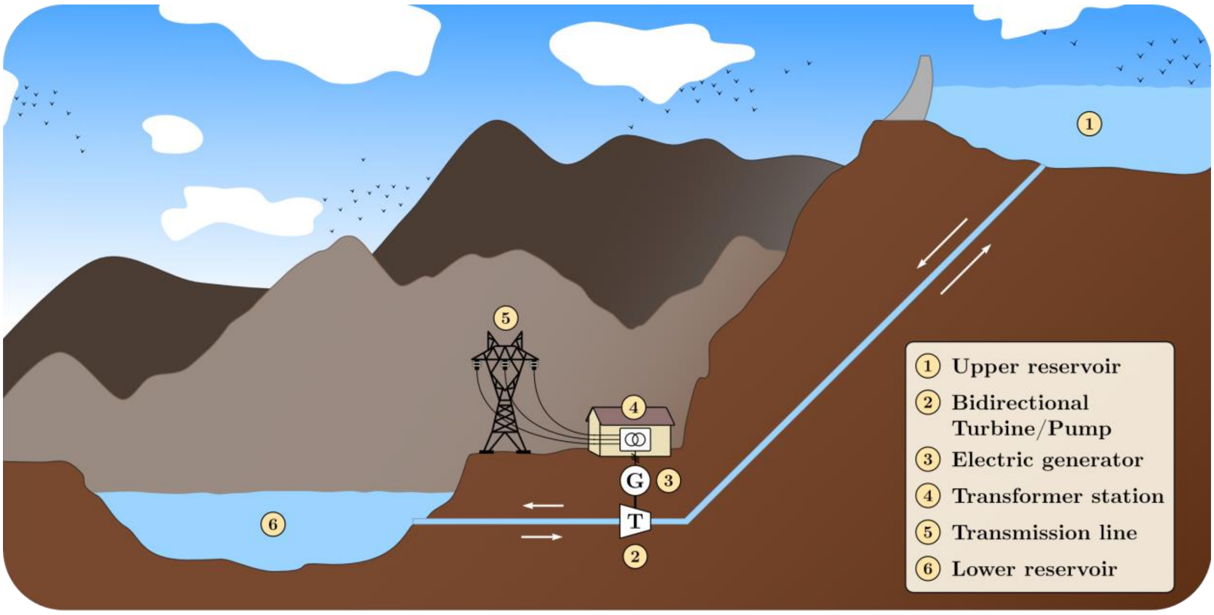


Figure 10. General scheme of a pumped-storage hydropower plant (PS-HPP)

Large hydropower schemes are well-known and broadly used for electricity generation. Water flows out of a reservoir and falls in height (effective head) in a controlled manner turning a turbine that drives an electrical generator. Since water availability is limited due to seasonal constraints, the energy can be stored (usually, 4 to 16 hours of continuous operation [21]) in order to generate power at times of high load. The main advantage of hydropower is its natural capability to store its primary energy resource (water) in large reservoirs. Besides, its response time (2-5 min [22]) makes this generation technology appropriate for following both predicted and unexpected changes in electrical demand. However, these schemes entail large capital investments and involve undesired environmental impacts such as flooding of large areas and population displacement. Furthermore, it is unlikely that this established renewable energy technology provides increased contributions in the future.

Small hydropower schemes, commonly defined as those being smaller than 5 MW, include small scale hydropower and run-of-river electrical generation. The former has a smaller head compared to the aforesaid schemes, and the latter extracts power predominantly from kinetic energy of a river flow, by means of turbines placed at effectively zero head. These schemes are particularly attractive for remote rural areas without a conventional electricity supply, since their energy requirements are consistent with the available resources. Seasonal constraints are also important.

In areas where the installation of large hydropower is unsuitable, pumped-storage hydropower is a promising alternative to consider. In Figure 10, a sketch of its main subsystems is shown. A PS-HPP station comprises an upper and a lower reservoir and a binary or ternary pumping-turbine set. Whenever electricity is needed, water is driven from the upper reservoir to the lower reservoir and electricity is generated via the turbine system. Its main advantage is that whenever there is an excess of electricity generation, water stored in the lower reservoir can be pumped back to the upper reservoir. Consequently, water gains gravitational potential energy that can be used in the future for electricity generation to meet the demand [22]. Since it enhances grid's flexibility, in the short term pumped-storage hydropower is expected to substantially extend.

As stated before, all hydropower systems exploit water's potential energy. There three main turbines distinguished by two working principles: impulse turbines (Pelton) and reaction turbines (Francis and Kaplan). Impulse turbines are suited for high pressure/head. Contrary, reaction turbines have greater speeds and are suited to lower heads. Turbine efficiency depends critically on specific speed, which in turn depends on the effective head and the relative speed of the runner blade relative to the water. For instance, reaction turbines use guide vanes at the rotor inlet to adjust the outcome shaft power in response to the electrical load.

1.3.2.4 Biomass energy

In a different manner than other renewable energy technologies, biomass energy encompasses all sorts of solid biomass (such as wood, crops, etc.) or liquid biofuels that can be stored and used for electricity generation, similarly as fossil fuels. Nevertheless, this sort of fuel has limited energy density. In order to reduce lifecycle CO_2 emissions footprint, energy consumption associated with transportation must be considered since in some cases it might exceed that of the fuel itself [18]. In order to illustrate this problem, Figure 11 depicts the life cycle of a biomass plant using wood as main fuel. As it can be seen, there can be several polluting agents during the whole process (lumber industry, transport, shipping, etc.). Ideally, biomass must be produced and consumed locally if possible (see right hand side of Figure 11). That is the reason why most biomass power plants rely on local feedstock and supply chain. Besides, their size is usually smaller than conventional power plants.

Regarding solid biomass, three thermochemical conversion technologies are distinguished: direct combustion, gasification and pyrolysis. On the other hand, liquid biomass is used for the production of methane via anaerobic digestion. These technologies are still under development so they are not competitive on price with conventional power generation based on fossil fuels. However, they are competitive with nuclear power or coal stations with carbon capture systems.

In the short term, the greatest potential is for embedded gasification or pyrolysis plants driving steam turbo generators. For instance, dedicated plants for rural industry or farms. Furthermore, for grid connected applications, larger embedded biomass generation stations, ranging from 1 MW to 20 MW approximately, could provide end-of-grid support to meet peak demands and avoid the grid to become overloaded and unreliable.

Assessing its environmental impact, it is vital to not underestimate the energy employed to grow the resource (planting, watering, pesticides, etc.), in this case, biomass. Regarding electricity generation, combined heat and power plants (CHP) or cogeneration plants present the highest efficiencies. Furthermore, if the biomass is grown organically and used locally, the compounded benefits are greater. In Europe and other similar latitudes miscanthus and willow are the preferred crops. On the other hand, large scale biofuel production could even have an adverse social and environmental impact due to its intense energy usage. In addition, expansion of biofuel crops could also accelerate tropical deforestation, reducing CO_2 absorption and menacing several species.

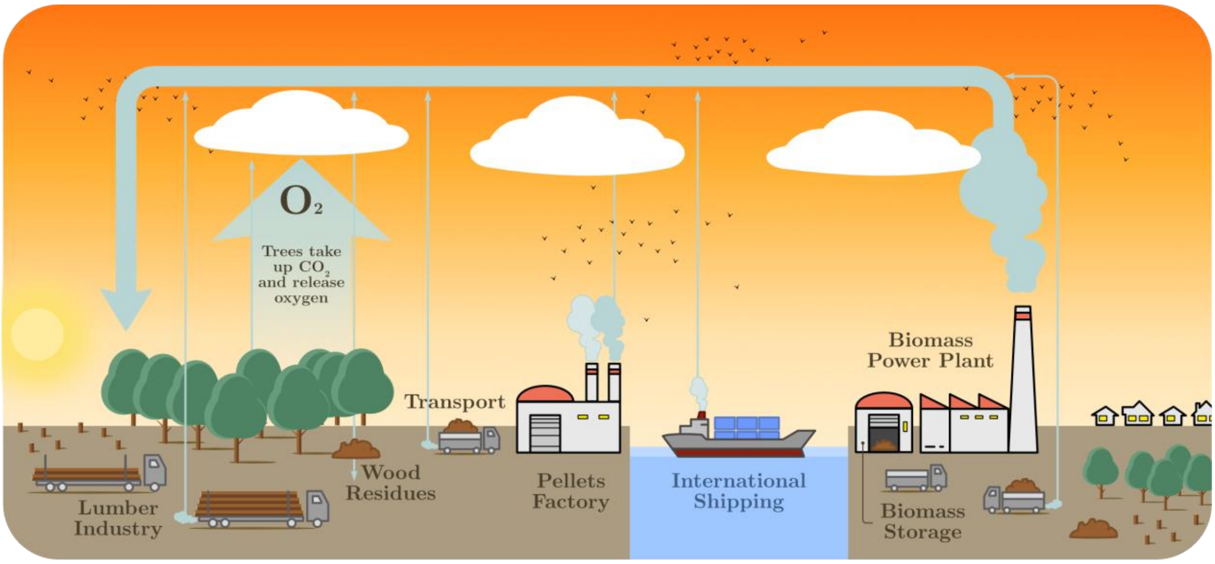


Figure 11. Conceptual scheme of the biomass resource process, including local generation and generation involving transport

1.3.2.5 Geothermal energy

Geothermal energy is heat derived within the sub-surface of the earth [23]. The heat transfer medium is water and/or steam. This renewable energy source is highly dependent on geographical locations, showing different characteristics. For electricity generation purposes, medium or high temperatures are required. Therefore, geothermal power generation stations are placed near tectonically active regions. Besides electricity generation, if the temperatures are low, heat can be used for heating greenhouses, buildings or districts.

Countries in possession of these geographical and topographic characteristics cover a significant share of their heat and electricity demand by means of this key renewable resource. For instance, Iceland covers more than 90% of their heating demand. This resource does not depend on weather conditions and has very high-capacity factors, so it can provide baseload power along with ancillary services to increase grid flexibility [23].

Like other power plants, geothermal power plants use steam to drive steam turbines to produce electricity. A basic scheme of a generic geothermal power plant which encompasses the different main subsystems (production wells, steam turbine, electric generator, etc.) is shown in Figure 12. There are three main types of geothermal power plants: dry steam, flash steam, and binary cycle.

On one hand, dry steam power plants pipe steam directly from underground wells into the turbine/generator unit. Unfortunately, this underground resource is scarce. On the other hand, flash steam plants are the most common ones. These plants extract water at around 182°C from underground geothermal reservoirs. Water flows upward by its own pressure and as it loses pressure it starts to boil. Then, only steam is used to drive the turbine and afterwards, any leftover (water or condensed steam) is injected back into the reservoir [24]. Finally, binary steam power plants pump water from underground reservoirs too. Nonetheless, instead of water (which temperature is around 107-182°C) they employ a working fluid to run the turbine so as to maintain acceptable overall plant efficiencies. Similarly, once water has cooled it is injected back to the ground. Nowadays, two types of geothermal resources are used in binary cycle power plants: enhanced geothermal systems (EGS) and low-temperature and co-produced resources.

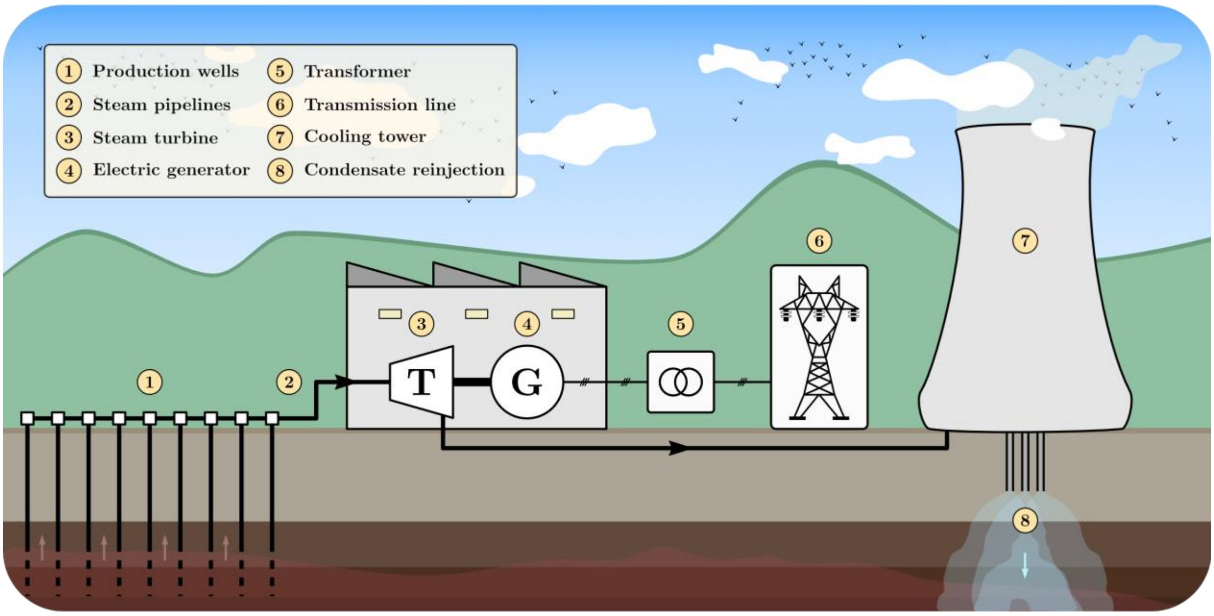


Figure 12. General scheme of a geothermal power plant

1.3.2.6 Thermal power

Conventional Coal Thermal Power Station

The main idea of the conventional thermal power plants is to obtain electricity from fossil fuels. This is based on a Rankine cycle (Figure 13).

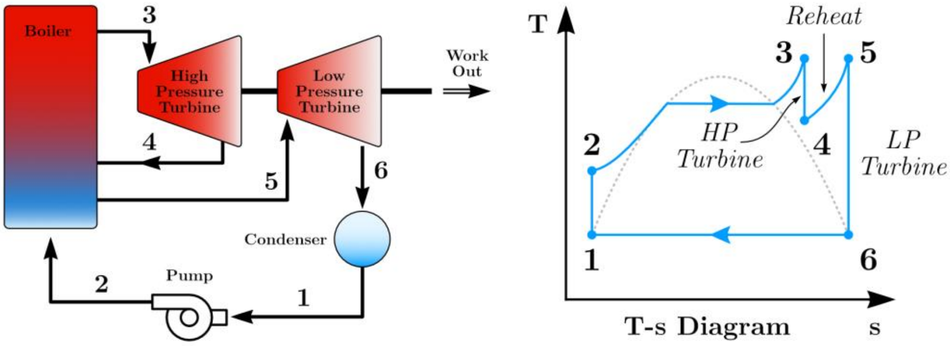


Figure 13. Rankine cycle and reheat

The process is described as follows. First, the coal (or fuel) is burned in the boiler, generating a large amount of heat in order to transform water into highly pressurized steam. After that, the pressurized steam generated in the boiler moves to the turbine chamber, which contains different sets of turbines (e.g. higher, medium and lower pressure) that effectively transform the steam into rotating power in the shaft. The rotation of the turbines and the fact that they are coupled to the electricity generator, make the mechanical-to-electrical transformation possible. The generated voltage is stepped up with a transformer, in order to transport the power at lower losses. The steam from the turbines section is circulated back to be transformed into water in the condenser, starting the cycle again [25]. The different parts of this type of power plant are shown in Figure 14.

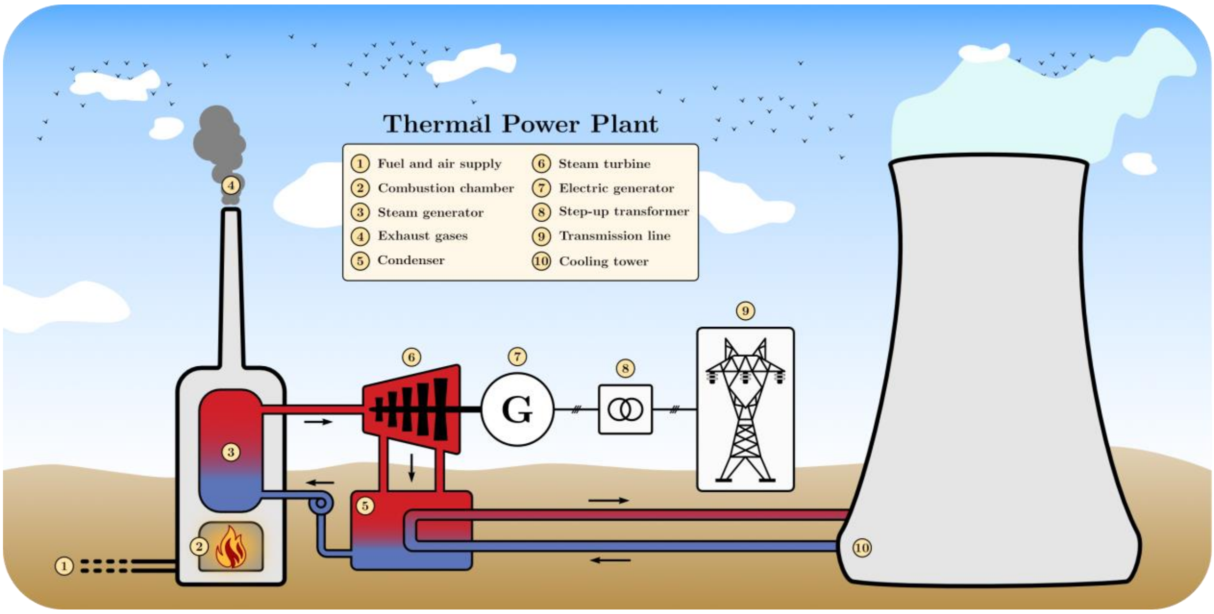


Figure 14. Conventional thermal power station

The idea of the steam cycle applies to all kinds of conventional power plants, independent of the fuel used. However, some differences exist in the preliminary treatment of the fuel and the design of the boiler burners. Therefore, in the case of coal-fired power plants, the coal needs to be crushed beforehand, in case of oil-fired power plants, the fuel is heated, and in case of natural gas, the gas arrives to the power plant through pipes, so no storage is needed.

Combined-Cycle Thermal Power Station

This type of thermal power plant operates following a similar principle as the coal or fuel plants. However, in that case the main fuel used is natural gas, and the process is split in two stages: one corresponding to the gas turbine (Brayton cycle, Figure 15) and one corresponding to the steam turbine, similarly as in the conventional thermal power plant (Rankine cycle, Figure 13).

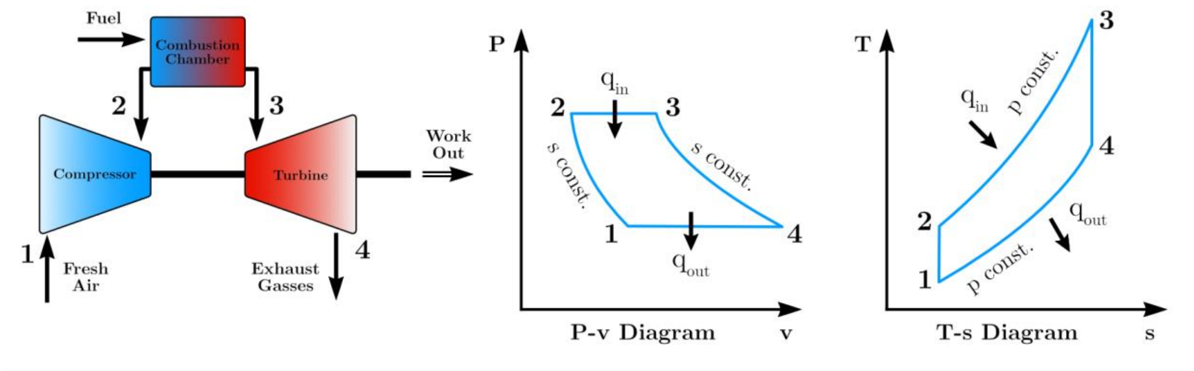


Figure 15. Brayton cycle

The process consists of the following steps. First, external air is compressed to high pressure using the compressor. From there, this air is brought to the combustion chamber, where it is mixed with the gas. After that, the combustion gas goes through the gas turbine, expanding itself, and converting heat to mechanical power. Next, the gas at the turbine's output moves to the recovery boiler, where steam is produced. Finally, the conventional steam cycle takes place. Typically, both turbines are coupled to the same shaft [26].

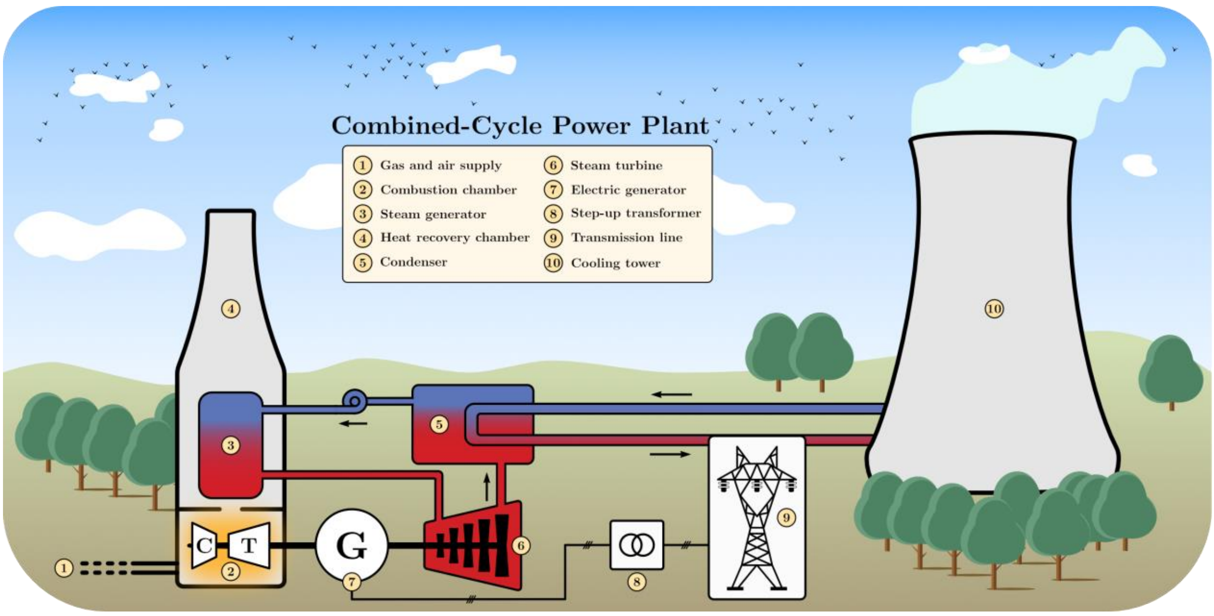


Figure 16. Combined-cycle thermal power station

This type of power plant is more flexible than the conventional thermal power plant, in the sense that it can operate at a wider range of powers (with a minimum power of around 45 % of the rated power of the plant). They are more efficient, the emissions are lower, and the consumption of refrigerating water is also lower. Their footprint is also smaller than the conventional ones, proportionally to the installed power. The different parts of this type of power plant are shown in Figure 16.

Nuclear power plant

The most common Nuclear Power Plant is the Pressurized Water Reactor (PWR) with 68% of the Nuclear Power Plants of the World (Figure 17). This kind of reactor uses the Rankine cycle (Figure 13) to produce electricity. In meaningful terms, the combustion chamber is changed for the reactor. The heat is generated by fissions in the reactor vessel, which contains water at 157 bar without boiling. This water extracts the heat from the core. In the steam generators (heat exchangers) the primary circuit shares the energy to the secondary circuit generating steam at 65 bar. This steam follows the Rankine cycle explained before. The reactor vessel and the primary circuit are located inside the containment building to prevent radioactivity dissemination and to protect the critical systems from outside. The operation cycle is about 18-24 months. Then a refueling is needed.

The fuel is enriched uranium at 3-5%, that means that 100 grams of fuel contain 3-5 grams of U-235 and the rest is U-238. The uranium that can fission in this type of rector is the U-235. The main advantage of nuclear power plants is the energy concentration of the fuel, 1 kg of fissioned U generates $3.3 \cdot 10^6$ more energy than a kg of burnt coal.

The spent fuel can be reprocessed or stored. It must be considered that the spent fuel has 3-4% of radioactive materials, which have to be stored and also contained if the spent fuel is repossessed. The decision of reprocessing or not the spent fuel is a Government decision.

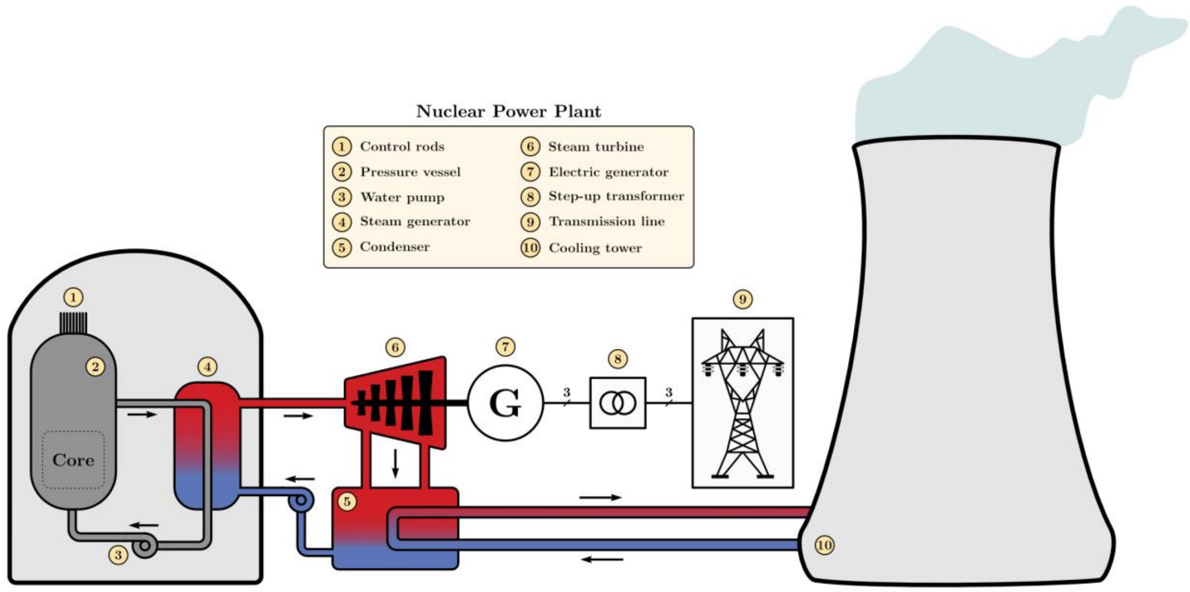


Figure 17. PWR nuclear power plant

1.3.3 Key definitions for analysis and comparison of different technologies

The following concepts are defined in order to allow a clear comparison of the different possible candidate technologies, in order to build relevant scenarios in the following chapter of the deliverable.

Controllability

Capability of an electricity generation technology to store and control the power exchange with the network.

Level definitions:

1. Non-storage capability. The resource defines the power injection to the grid. It can be only curtailed, but not stored unless additional equipment is used.
2. Limited storage of the converted energy. Example: thermal energy in solar thermal power plants can be stored.
3. Storage of primary energy - Low capacity
4. Storage of primary energy - Medium capacity
5. Storage of primary energy - High capacity

Dispatchability

Capability of an electricity generation technology to provide power based on the operation set-point [27].

Level definitions:

1. The primary energy availability permanently constraints the power output capability.
2. The primary energy availability constraints the power output capability, but the power can exceed the threshold temporarily (short time-seconds)
3. The primary energy availability influences the power output capability. However, the power output can be increased by means of a secondary (inherent storage) energy source.
4. The primary energy availability is sufficient to not constrain the output power.
5. The primary energy availability does not constraint the power output capability and it is possible to reverse the power plant to produce primary energy from the surplus of electricity in the network (bidirectional capability).

Response time

The time elapsed between the acknowledgement of a new power reference and its successful tracking.

Inherent storage Time

Total amount of time that an electricity generation technology can provide electricity at full capacity by means of its inherent energy storage [28].

CO_2 Emissions

Amount of CO_2 grams per kWh produced by an electricity generation technology considering its lifecycle footprint.

Levelized cost of electricity (LCOE)

Average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle [29].

Capital expenditure (CAPEX)

Funds used by a company to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment [30].

Operational expenditure (OPEX)

Expenses related to the production of goods and services [31].

1.3.4 Summary

To sum up with the work presented in Section 1.3, the following tables collect the most relevant features of each technology regarding technical characteristics, costs and emissions (see definitions in Subsection 1.3.3).

On one hand, Table 1 displays the response time, inherent storage time, controllability, dispatchability and generation technology. These aspects determine the role that each technology may have within the electric power system. PV and wind present fast response times (from milliseconds to a few seconds), whereas the other technologies are much slower as they are solely based on synchronous generators. However, the inherent storage time of PV and wind is zero, whereas the other technologies offer this characteristic, from hours to months (conventional plants).

	Response time	**Inherent storage time**	**Controllability [1-5]**	**Dispatchability [1-5]**	**Generation technology**
PV	100 ms - 5 s [32]	0	1	1	PE
ST	15 min – 4 h (1) [33]	0 - 24 hours [34]	2	3	SG
W	0.5 ms - 1 s [20]	0	1	2	SG/IG+PE
HYD	2 - 5 min [22]	4h - 16h [21]	3	4	SG
BIO	10 min – 6 h (2) [33]	Weeks	4	4	SG
CF-TPS	80 min - 8 h [35]	Months	5	4	SG
CC-TPS	5 min – 3 h [35]	Months	5	4	SG
N-TPS	~24 h [33]	18-24 Months	5	4	SG
PS-HPP	2 - 5 min [22]	4h - 16h [21]	3	5	SG
GEO	30 s – 2 min	inf	5	4	SG

(1) Ramping rate: 6% of full load/min. Hot start-up time: 2.5 h
(2) Ramping rate: 8% of full load/min. Hot start-up time: 3 h

Legend: PV: solar photovoltaic – ST: solar thermal – W: wind – HYD: hydropower – BIO: biomass – CF-TPS: coal-fired thermal power station – CC-TPS: combined-cycle thermal power station – N-TPS: nuclear thermal power station – PS-HPP: pumped-storage hydropower plant – GEO: geothermal – PE: power electronics – SG: synchronous generator – IG: induction generator.

Table 1. Technical characteristics of the different generation technologies considered

On the other hand, Table 2 shows costs, revenues and emissions associated with each technology: LCOE, CAPEX, OPEX, fuel cost and CO_2 emissions extracted from up to date reports. Some of these values will be used later on in Section 3 to carry out the optimization for the sizing of the scenarios.

	LCOE [$/kWh]	**CAPEX** [36] **[$/kW]**	**OPEX** [36] **[$/kW]**	**Fuel cost**	**CO_2 Emissions** [37] [38] **[g-eq/kWh]**
PV	0.029 to 0.042 [39]	1313	15.25	0	18 to 180
ST	0.126-0.156 [39]	7221	85.40	0	9 to 63
W	0.026 to 0.054 (onshore), 0.086 (offshore) [39]	1265 to 4375	26.34 to 110	0	8 to 40
HYD	0.0473 [40]	5316	29.86	0	2 to 200
BIO	0.0656 [40]	4097	27.47	20-50% LCOE	50 to 400
CF-TPS	0.065 to 0.159 [39]	3676 to 5876	40.58 to 59.54	42.47 $/t [41]	850 to 1125
CC-TPS	0.044 to 0.073 [39]	958 to 2481	12.20 to 27.60	0.106 $/m^3 [42]	450 to 525
N-TPS	0.129 to 0.198 [39]	6041 to 6191	95.00 to 125.72	3-5 €/MWh [43]	15 to 30
PS-HPP	0.0473 [40]	5316	29.86	0	2 to 200
GEO	0.059 to 0.101 [39]	2521	129.70	0	50

Table 2. Costs and emissions of the different generation technologies considered

1.4 Generic analysis of the availability of resources in Europe

Europe has an abundance of renewable energy resources. The knowledge of RES and its spatial distribution is fundamental in defining scenarios for different energy mix based on renewables.

1.4.1 Solar resource

The knowledge of the spatial and temporal distribution of solar resources is a first step in all aspects of solar systems projects and deployments. Indeed, energy policy decisions, engineering designs and system deployment considerations require an accurate understanding of the spatial variability of solar resources [44]. Despite ground stations measuring solar radiation are in continuous growth its spatial density is still insufficient to proper spatial characterization of solar resources. Therefore, solar radiation data for energy applications is generally obtained from satellite derived and numerical weather models that supply complete time series of spatially gridded data.

Nowadays, there are many available services delivering high quality data of solar radiation components based on geostationary satellite information. One good example of these services with extensive uses along Europe is PVGIS database (https://ec.europa.eu/jrc/en/pvgis) which offers PV potential for different technologies, solar radiation data and maps with several aggregated data and Typical Meteorological Years (TMY) [45], [46]. Figure 18 shows the solar resources available in Europe according to PVGIS information.

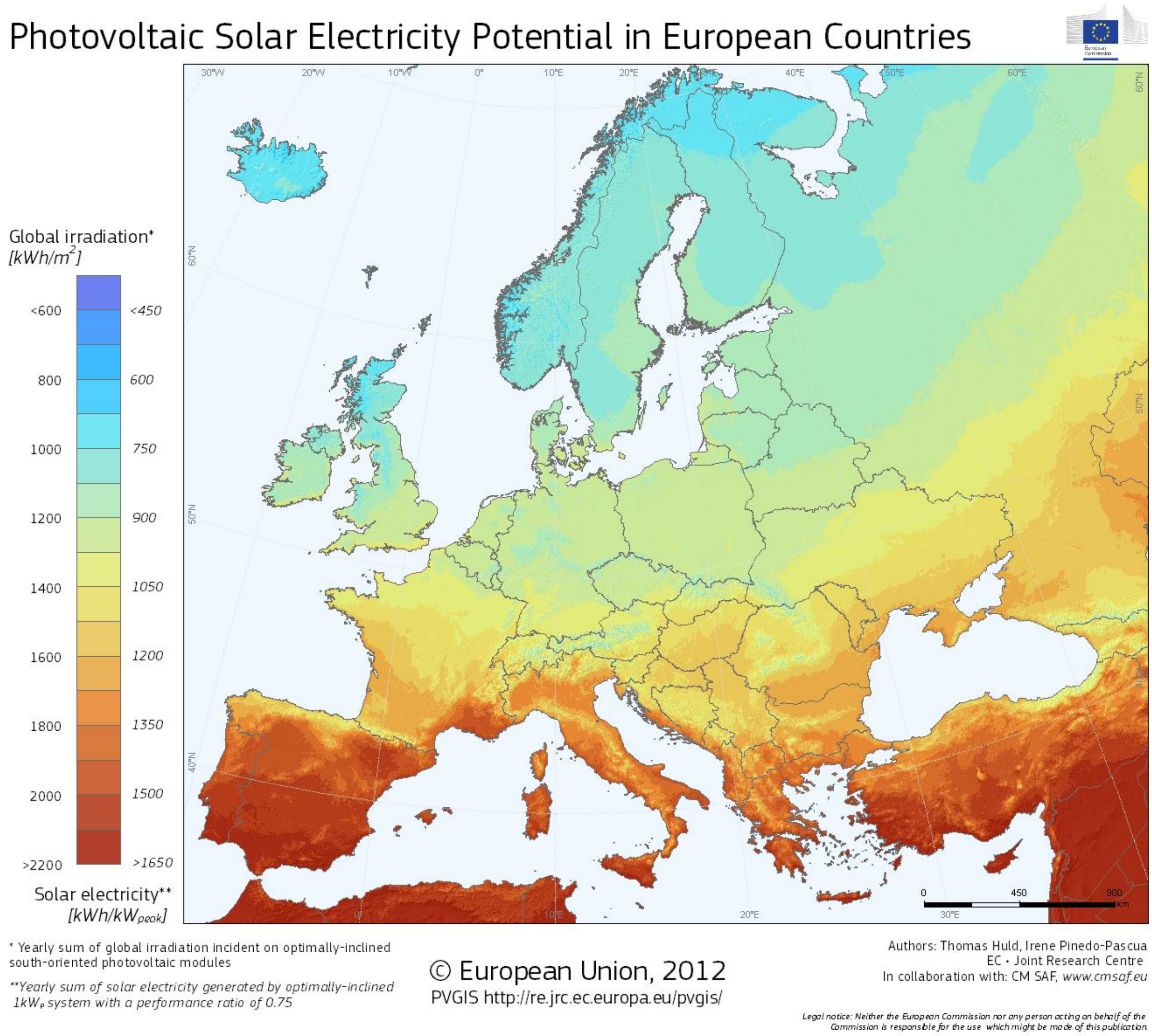


Figure 18. Solar resource distribution in Europe (from PVGIS web service)

Depending on the solar technology the required solar data may refer to a different component. Thus, for PV applications it is normally needed the knowledge of global irradiation, in particular the component named as POA (Plane of Array), which refers to the global incident irradiation to the PV surface. In the case of concentrated solar power systems (CSP) the required component is the direct normal irradiation (DNI). Satellite-derived models and services are delivering normally three components of the solar radiation: global horizontal (GHI), direct normal (DNI) and sky diffuse (DIF). DNI exhibits generally more variability than GHI, it is a component with higher sensitivity to clouds (direct normal drop to zero in cloudy overcast situations) and to the atmospheric aerosol loads. Therefore, only the south of Europe achieves enough level of DNI for proper exploitation of CSP power systems (Annual Cumulative DNI values for considering a site > 1600 kWh/(m^2 · year)).

Several high-quality services of solar radiation data have been developed within Europe through different EU projects and initiatives. Nowadays it can be remarked PVGIS, CM SAF (https://www.cmsaf.eu/EN/Home/home_node.html) and CAMS (Copernicus Atmosphere Monitoring Service, http://www.soda-pro.com/es/web-services/radiation/cams-radiation-service) radiation service as important sources of data of high quality that can be used effectively in prospecting PV and CSP applications in Europe [47], [48].

Due to its flexibility and simplicity in use, the web service Reneables.ninja (https://www.renewables.ninja/) has been used in the preliminary simulations described in this report. This web service allows for running simulations of hourly power PV and wind power plants, covering the whole world geography. Regarding solar data, Renewables.ninja includes two databases: CM SAF SARAH collection (for the period 2000-2015), and MERRA-2 reanalysis, with information until 2019. In addition to the PV power output, the user can download the raw data consisting on the hourly values of the solar radiation components.

1.4.2 Wind resource

Although the common practice in the development of wind farms is performing a site assessment through a wind resource campaign (see for example [49]), over the last 30 years numerous wind atlas have been calculated with coverage over the European region either wholly or in part. The last and most complete one is the NEWA, New European Wind Atlas, which will be shortly introduced now. Apart from this European Wind Atlas, there is also a Global Wind Atlas which is valid not only for Europe, but for any area in the world, also introduced in this chapter. Both of them are freely accessible, and in both of them the off-shore wind resource is also shown, along with the traditional onshore wind resource.

1.4.2.1 New European Wind Atlas

The European Wind Atlas (https://map.neweuropeanwindatlas.eu/) was the first comprehensive wind atlas publication covering a number of European countries. It used the newly developed modelling elements within WAsP (Wind Atlas Analysis and Application Program) [50] to calculate generalized wind climates (WAsP lib-file) from wind measurement data at large number of European measurement sites. The generalized wind climates can then be applied to nearby new sites.

The European Wind Atlas is the predecessor to the New European Wind Atlas (NEWA), so it sets a historic standard for usability of the data and method and documentation of the method itself.

The NEWA wind atlas consists of mesoscale and microscale datasets that cover all European Union member-states, Norway, Switzerland, the Balkans, and Turkey. The mesoscale atlas was made using the Weather Research and Forecasting (WRF) model and includes a number of both surface and boundary layer meteorological variables with a 3 × 3 km grid-spacing. The resulting data are available at seven wind energy relevant heights for 30 minutes intervals over a 30 years period from 1989 to 2018. The WRF model output was downscaled using the WRF-WAsP methodology to create the microscale atlas, which is a high-resolution atlas of the statistical wind climate covering the regions in a 50 × 50 m grid (see Figure 19).

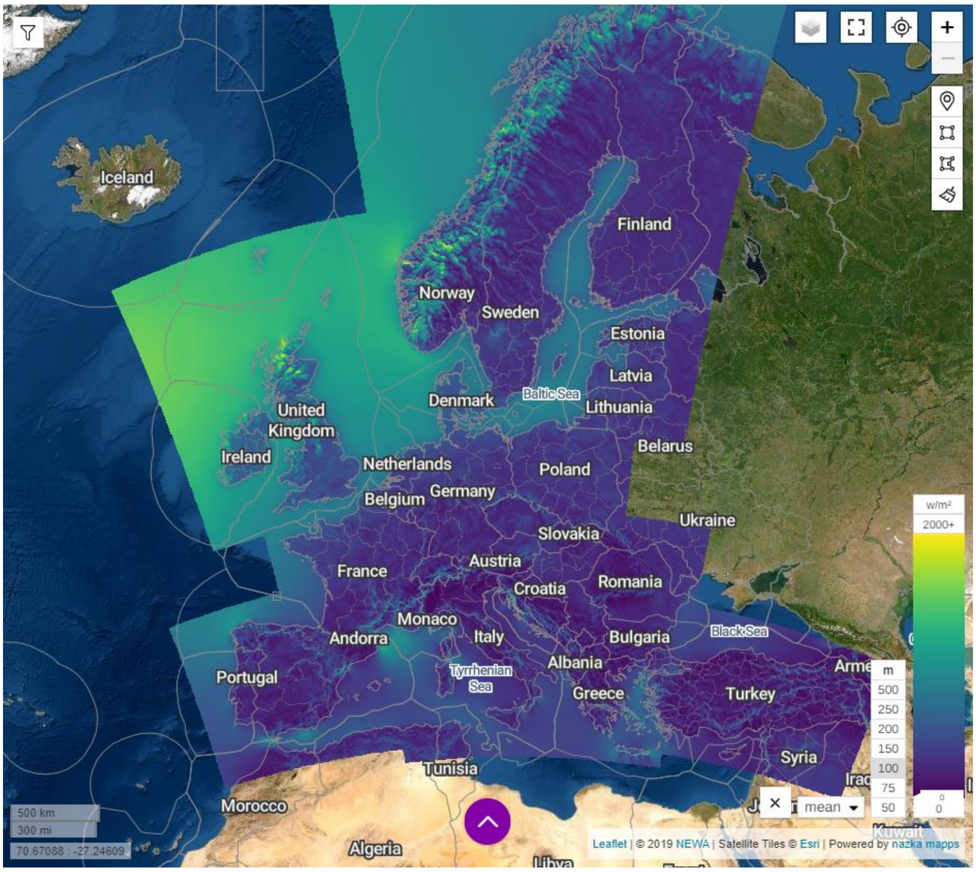


Figure 19. Screenshot of NEWA (https://map.neweuropeanwindatlas.eu/) (Date: 11/03/2021)

1.4.2.2 Global Wind Atlas

The first version of the Global Wind Atlas (https://globalwindatlas.info/) was a modelling based wind atlas using input data from MERRA (Modern Era Retrospective-Analysis for Research and Applications) reanalysis downscaled directly to microscale using a WAsP based calculation system, with roughness length derived from Globcover land uses classes and surface elevation from ViewFinder terrain dataset, and it was funded by the Danish Energy Agency.

On the other hand, the existing Global Wind Atlas is an update on the previous version, and is a modelling based wind atlas using input data from ERA-Interim reanalysis downscaled via mesoscale modelling using WRF and then to microscale using a WAsP based calculation system, with roughness length derived from Globcover land uses classes and surface elevation from ViewFinder terrain dataset (See Figure 20). This one was funded by the World Bank.

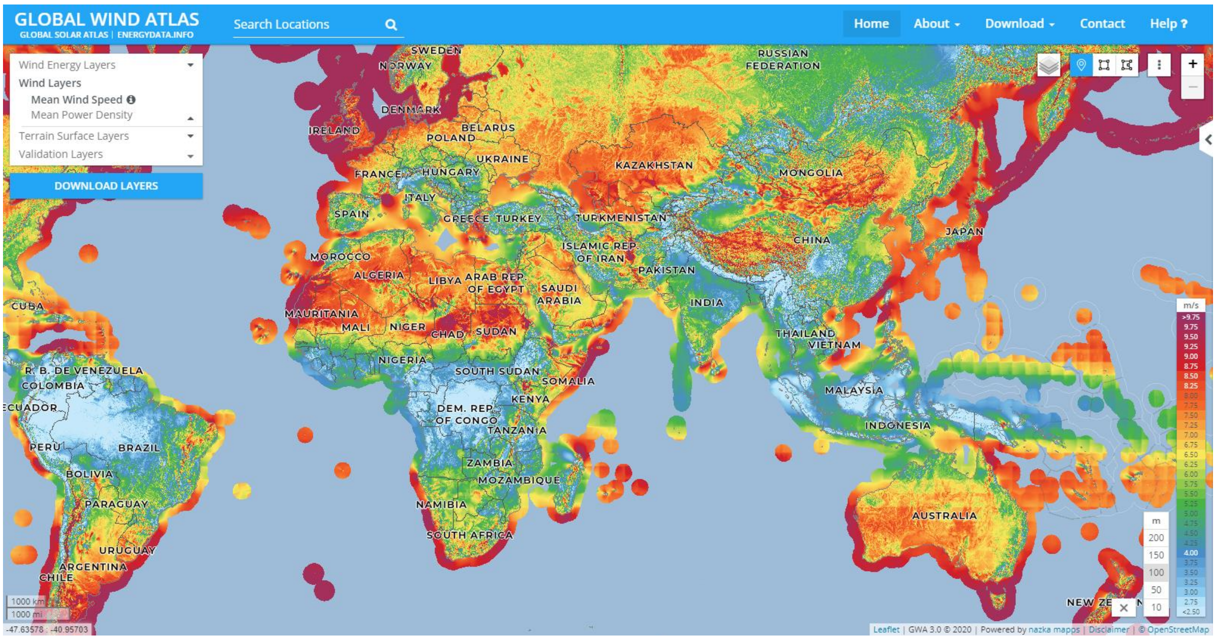


Figure 20. Screenshot of Global Wind Atlas (https://globalwindatlas.info/) (Date: 11/03/2021)

Renewables Ninja web service, which has been mentioned before, allows the modeling of wind power plant simulations in an hourly basis, including several turbine models that can be selected by the user. The service also offers the wind speed derived from the MERRA-2 reanalysis (1980-2019).

1.4.3 Biomass resource

Biomass is any organic matters from plants or animals and is thus a renewable energy source. Biomass for energy can be in solid, liquid or gaseous form including or not fuel processing steps. Biomass can be collected from many sources as for examples:

- • Forests, such as firewood or logging residues.
- • By-products of the wood industry (e.g. bark, saw dust, shavings, black liquor).
- • Energy crops (e.g. arable crops: cereal or oil based; perennial lignocellulosic crops: woody and grassy).
- • Agricultural by-products (e.g. straw, manure, orchards pruning, pruning).
- • Biomass from waste streams (e.g. municipal waste, animal by-products).
- • By-products from agro-food industry.
- • Aquatic biomass (algae).

Existing studies have calculated the domestically available potential for biomass for energy or bioenergy, to be between 169 and 737 Mtoe each year in Europe from 2050 onwards (Figure 21). A literature review concludes that the middle range potential of 406 Mtoe, which is around 24% of the total energy consumption in EU-28 in 2017, can be achieved by 2050 – considering different constraints (e.g. costs). This means that, compared to 144 Mtoe used in 2017, the potential gives enough room to almost triple the amount of bioenergy in the EU-28 energy mix.

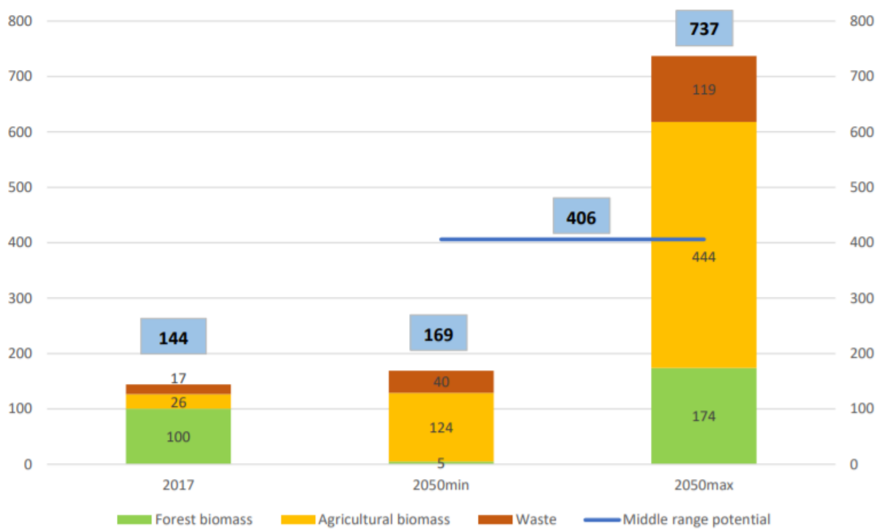


Figure 21. Gross inland energy consumption of biomass in 2017 and potential in 2050 for the EU28 (in Mtoe) [48]

Unused and abandoned areas represent 15.8% of the total land use in the EU28 which is significant amount of land that could potentially be used to grow energy crops. Croatia, Greece, Spain or the United Kingdom present high percentages of unused and abandoned areas (>25%). Additionally, Cyprus and Malta also have high shares of unused and abandoned areas, but the absolute figure is rather small. In absolute terms the countries showing the biggest unused and abandoned area are Spain, Sweden, Italy, France and the United Kingdom. Regarding the forest area proportions within the total area, Finland, Sweden and Slovenia are the top three countries while, in absolute terms, the top 3 with the largest forest area are Sweden, Finland and France.

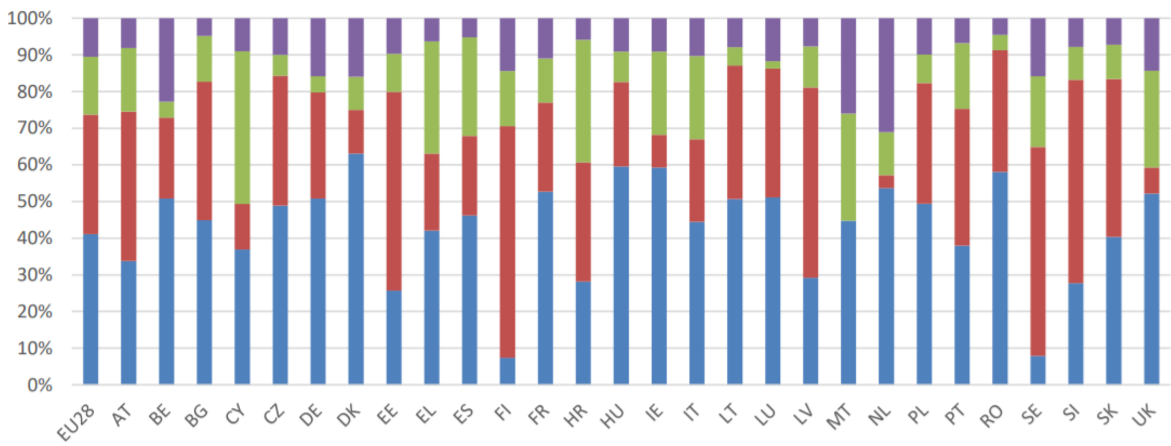


Figure 22. Land Use by type in EU28 2015 (%) [48]

According to data from 2016 [51], in terms of end use of bioenergy, the largest sector is heating and cooling (H&C), with about a 75% of all bioenergy consumed (Figure 23).

On the other hand, bioelectricity and transport biofuels reach about 13% and 12% respectively.

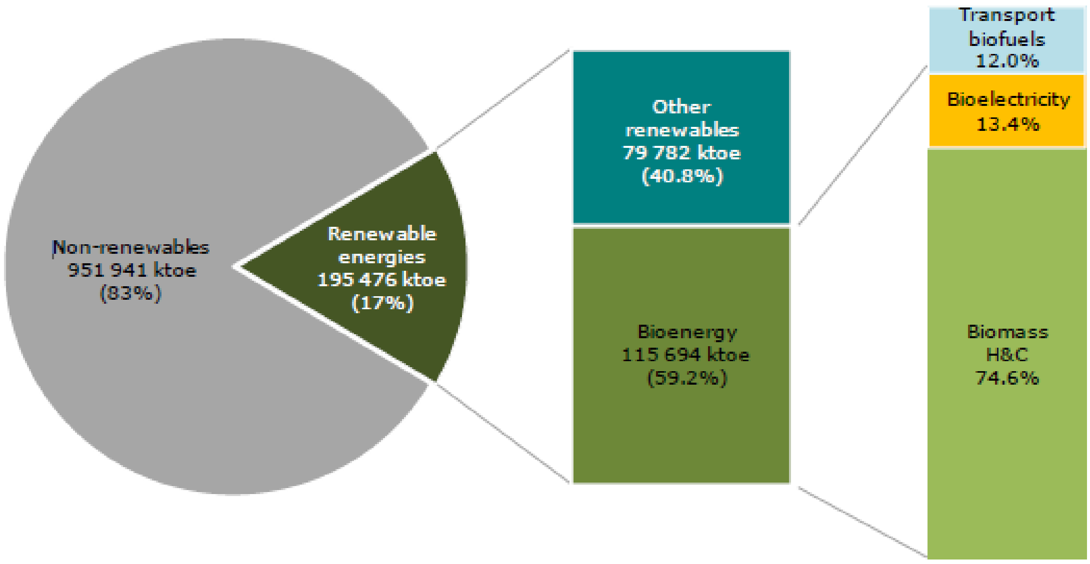


Figure 23. Share of renewables in the EU's gross final energy consumption for 2016 and breakdown of the bioenergy contribution

Within the bioenergy sector, bioelectricity has experienced the most significant relative growth over the period 2005-2016 (about 160% increase at EU level). In 2016, Germany, the UK, Italy, Finland and Sweden were the largest bioelectricity consumers (Figure 24).

Bioenergy can play a significant role as a flexible producer, allowing higher shares of variable renewable energy sources (solar and wind), in the electricity grid. Hybridation of bioenergy with solar thermal, concentrated solar power, heat pumps or waste heat recovery can ensure flexible options for both energy (heat and power) supply and energy storage.

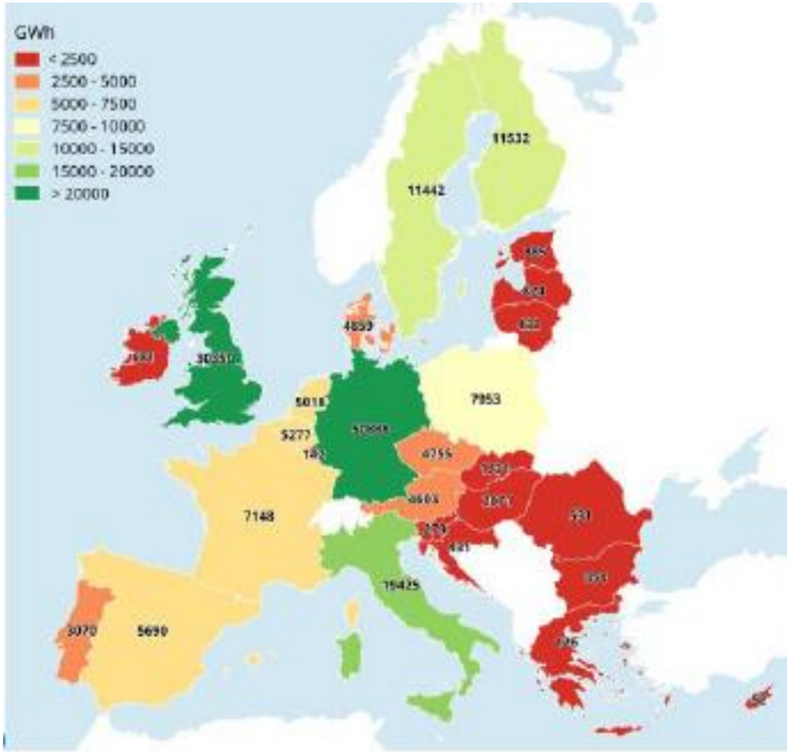


Figure 24. Gross final consumption of bioelectricity in EU Member States in 2016

1.4.4 Hydropower plants

Hydroelectric energy, also called hydroelectric power or hydroelectricity, is a form of energy that leverages the power of water in motion to generate electricity.

Depending on the technology, there are three different types of hydropower facilities: impoundment, diversion or run-of-river, and pumped-storage hydropower plant (PS-HPP). The most common type of hydropower is an impoundment facility, where a dam is used to control the flow of water stored in a pool or reservoir. When energy is needed, water is released from the dam, flowing through a turbine and powering a generator to produce electricity. The diversion facility uses a series of canals to channel a portion of river water toward the generator-powering turbines. It may not require the use of a dam. Finally, the PS-HPP stores the energy produced from solar, wind, and nuclear power, for future use. The plant pumps water from a pool at a lower elevation to a reservoir located at a higher elevation, using waste energy when the demand for electricity is low. When there is demand for electricity, water located in the higher pool is released back to the lower reservoir, running a turbine and generating electricity.

Over the last five years hydropower has grown by around 10 GW (5 per cent) across the European continent [52] even though annual generation has been variable in different regions, with a reduction due to a drier weather in southern countries. As an established sector in Europe, in 2019 capacity remained relatively stable with a total installed capacity of 251 GW (55 GW in PS-HPP).

The distribution of impoundment hydropower plants in Europe, classifying by size and conditions (existing dams, dams under construction and future dams), is shown in Figure 25.

The installed capacity in the continent is very irregular (Figure 26). Only 5 countries of the 43 in Europe have a capacity above 20 GW and 14 countries have a capacity below 1 GW.

In recent years, south Eastern Europe has gained attention for its significant hydropower potential, with sites identified across the Balkans as it is shown in the red dots of Figure 25.

Even though the growth capacity in Europe is limited compared to other areas, the actions to increase it will be focused on: new pumped-storage hydropower, development of small-scale hydropower or the transformation of dams in hydropower plants. There is growing research on pumped-storage hydropower with disused mines and underground caverns. To face environmental opposition in many countries to construction of large dams, small-scale hydropower has also been identified for development of new facilities. And finally, many dams were built for other purposes (recreation, stock/farm ponds, flood control, water supply, and irrigation) and they can be transformed in hydropower plants by adding a turbine and the power system (Figure 27).

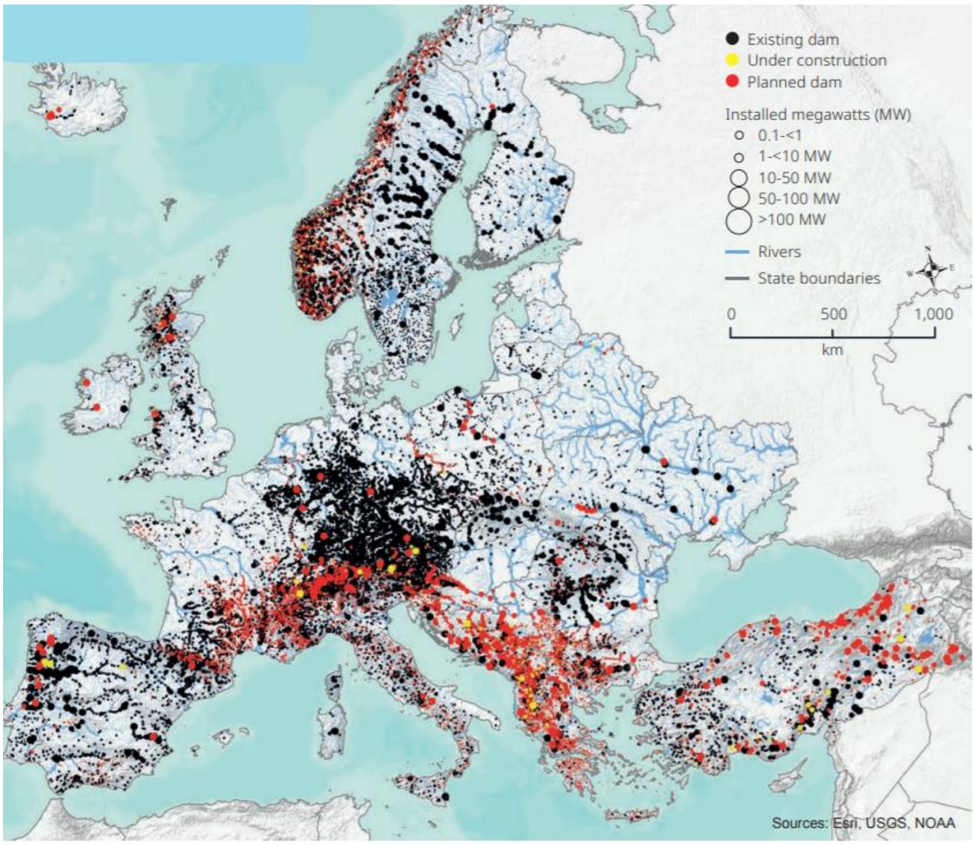


Figure 25. Distribution of hydropower plants in Europe, sorted by size and condition [51]

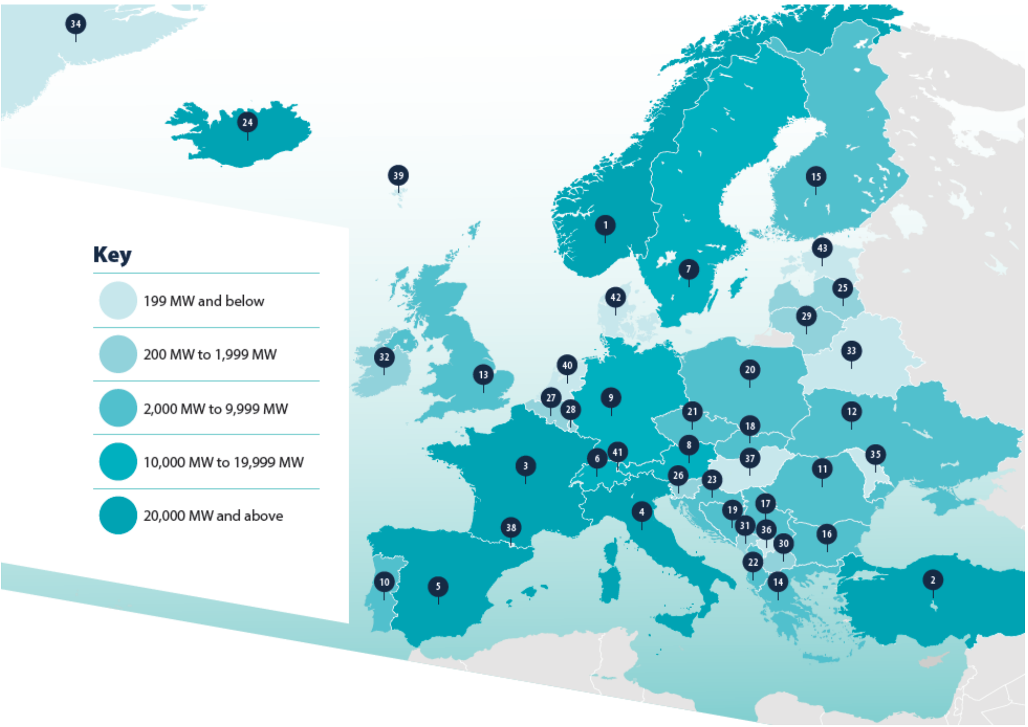


Figure 26. Europe overview of installed hydropower capacity

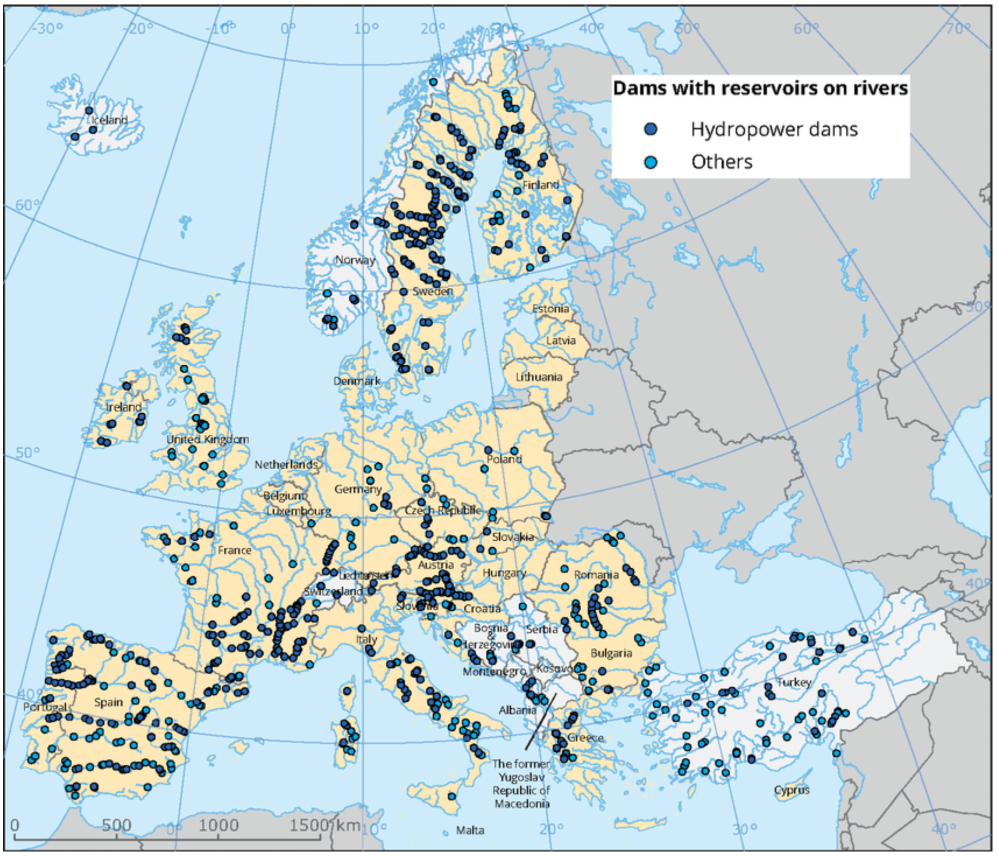


Figure 27. Dams on larger rivers in Europe. Hydropower stations and non-powered dams (NPDs) [52]

2 Scenarios

2.1 Scenario definition

The following preliminary characteristics are considered in the definition of the scenarios:

- A scenario will be inside a grid operation area
- One or multiple DVPPs can be considered
- The classification criteria are defined as follows:
  - Three main grid configurations:
    - Type I: Isolated
    - Type II: Synchronously interconnected (AC)
    - Type III: Non-synchronously interconnected (DC) (i.e. isolated systems with only DC interconnection/s)
  - Combination of different renewable technologies considering:
    - Different portion of renewable energy in the system
    - Controllable and non-controllable technologies
    - Consider power electronics in the generation plants
  - In terms of grid layout, only transmission, or transmission plus distribution
  - Optionally, non-electrochemical storage can be included
  - Dispatchable loads are not considered in this scenario definition

2.2 Generation of scenarios

A large number of scenarios can be generated based on the desired characteristics mentioned above. A first set of base case scenarios is proposed, offering a wide variety of cases, based on the three main types (I, II and II) and the following optional characteristics: distribution, synchronous generation, and storage. New scenarios can be easily generated modifying the initial ones. Different technologies have been included, although not all of them.

Note that the (non-electrochemical) storage element is optional, and each scheme represents two possible scenarios (with and without storage). Also note the following initial requirements:

- AC transmission networks are all meshed
- In AC interconnected DVPPs (Type II) two neighbouring AC networks are considered
- Biomass is in general only connected to distribution networks

These initial sketches are meant to be used as a starting point and as base scenario cases. Note that the DVPP is not specified, as different elements from the sketches could conform the DVPP, resulting in different alternatives (e.g., DVPP with more or less elements).

Type	Distribution	Conv. thermal synchronous generation	Storage	**Scenario**
Type I: isolated	YES	YES	YES	**1**
			NO	**2**
		NO	YES	**3**
			NO	**4**
	NO	YES	YES	**5**
			NO	**6**
		NO	YES	**7**
			NO	**8**
Type II: AC interconnected	YES	YES	YES	**9**
			NO	**10**
		NO	YES	**11**
			NO	**12**
	NO	YES	YES	**13**
			NO	**14**
		NO	YES	**15**
			NO	**16**
Type III: DC interconnected	YES	YES	YES	**17**
			NO	**18**
		NO	YES	**19**
			NO	**10**
	NO	YES	YES	**21**
			NO	**22**
		NO	YES	**23**
			NO	**24**

Table 3. Initial set of scenarios based on the combination of 4 characteristics

The following legend shows all the different elements used in the sketches of the scenarios:

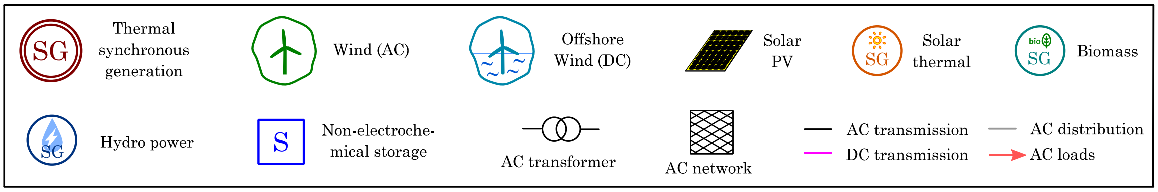


Figure 28. Legend used in the initial scenario sketches

The sketches of type I scenarios are shown in Figure 29-Figure 32.

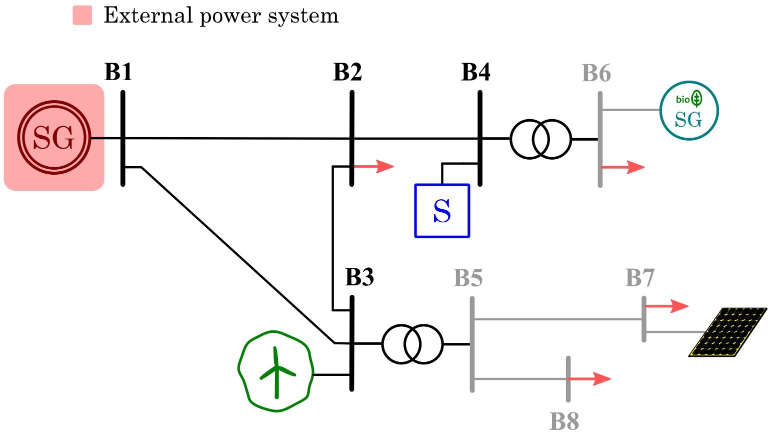


Figure 29. Sketch of scenarios 1-2 (type I)

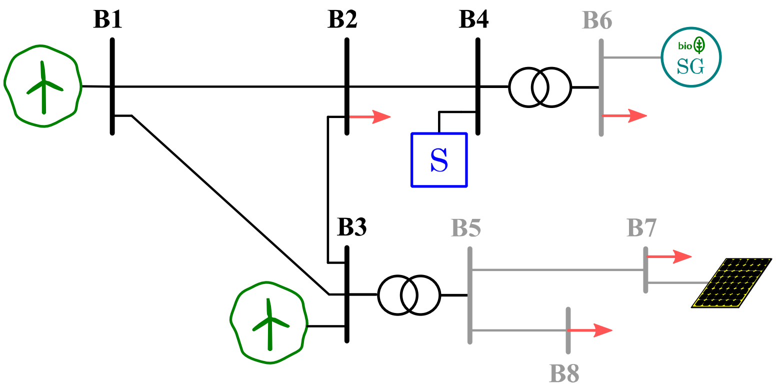


Figure 30. Sketch of scenarios 3-4 (type I)

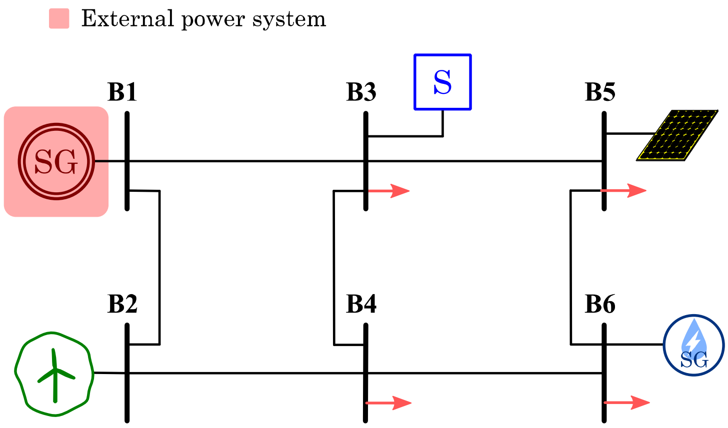


Figure 31. Sketch of scenarios 5-6 (type I)

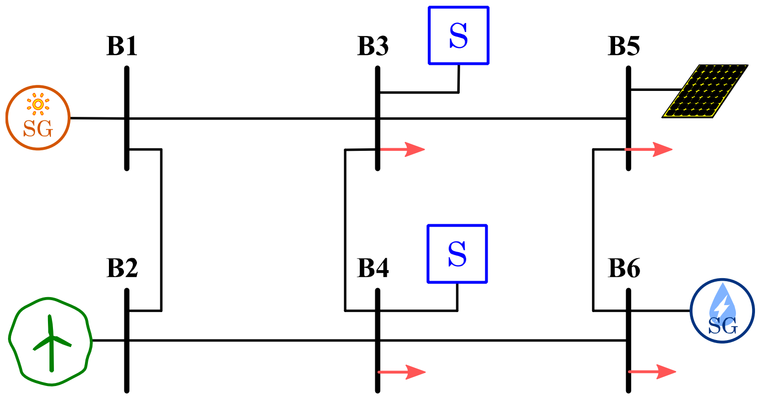


Figure 32. Sketch of scenarios 7-8 (type I)

The sketches of type II scenarios are shown in Figure 33-Figure 36.

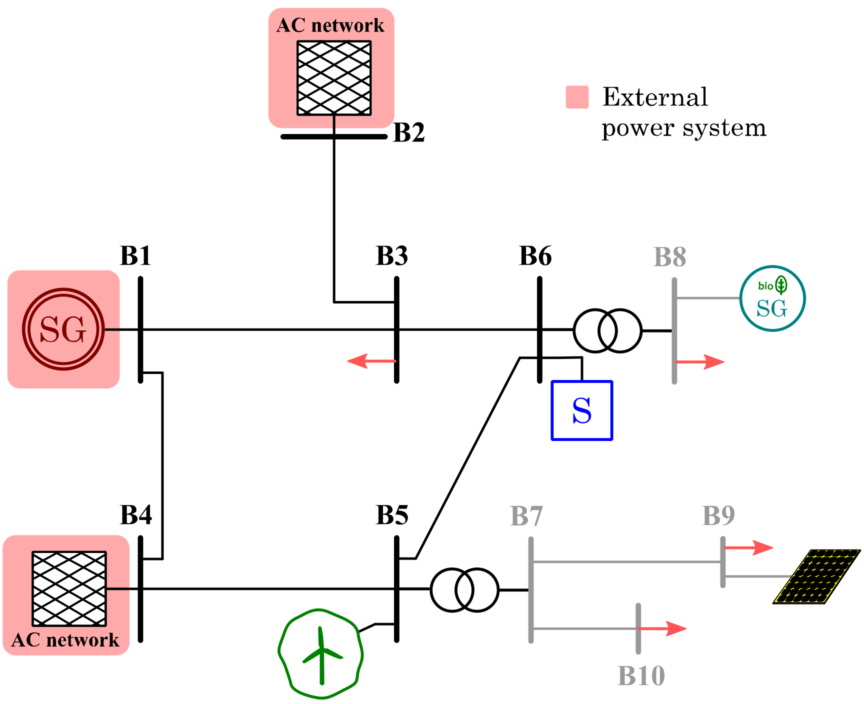


Figure 33. Sketch of scenarios 9-10 (type II)

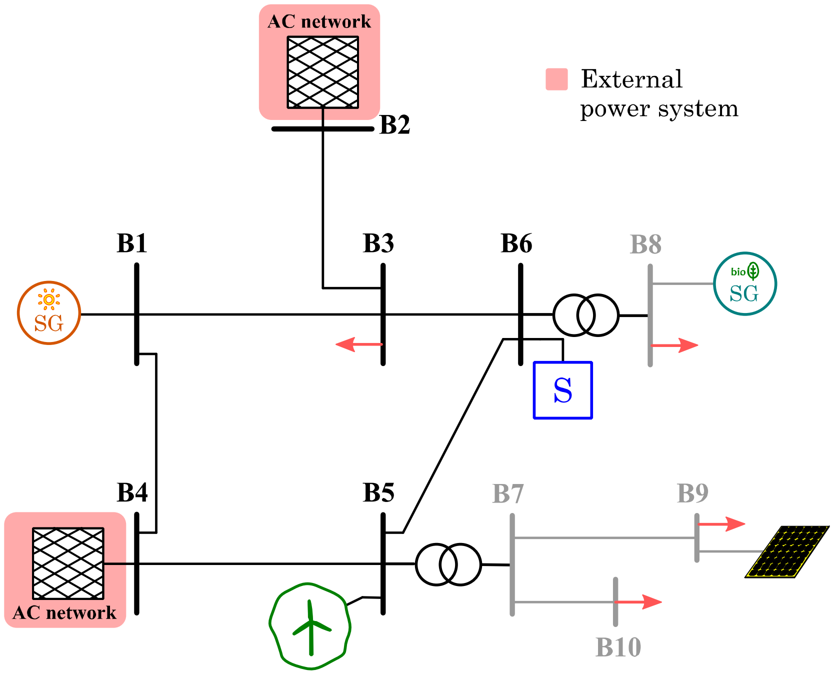


Figure 34. Sketch of scenarios 11-12 (type II)

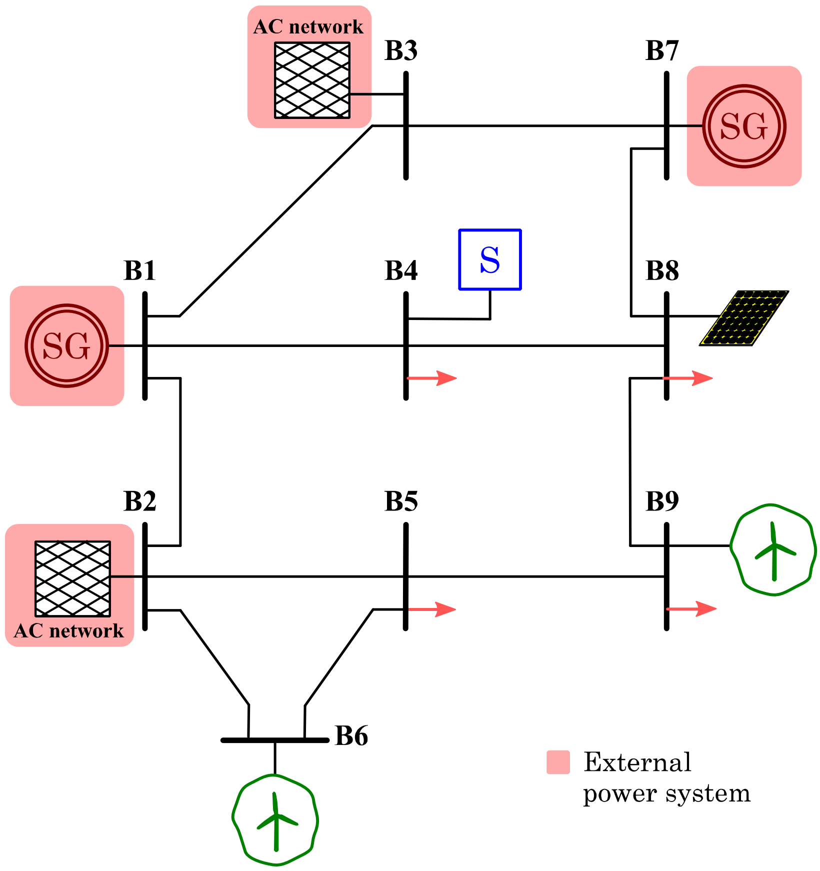


Figure 35. Sketch of scenarios 13-14 (type II)

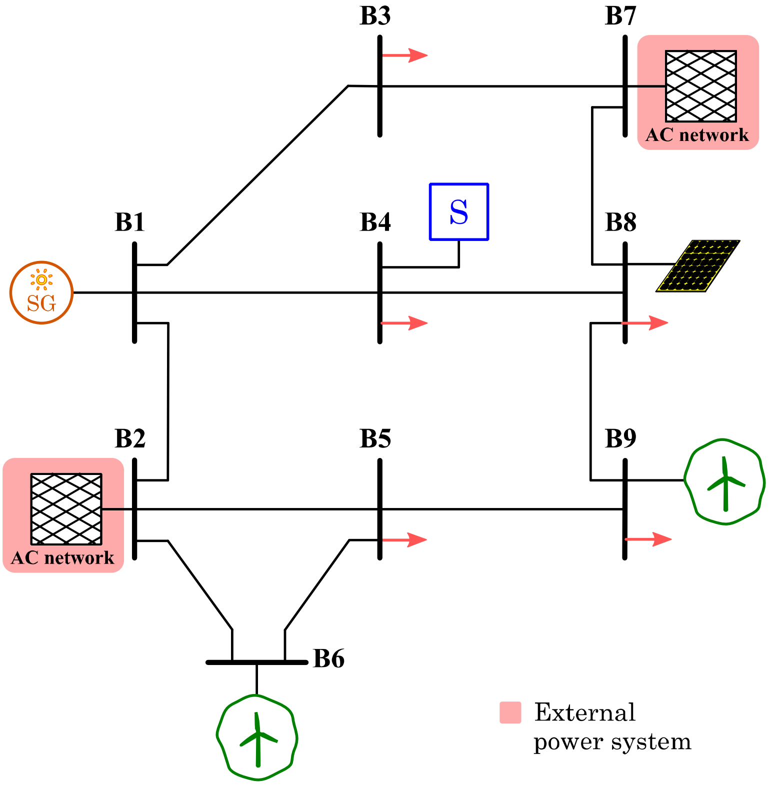


Figure 36. Sketch of scenarios 15-16 (type II)

The sketches of type III scenarios are shown in Figure 37-Figure 40.

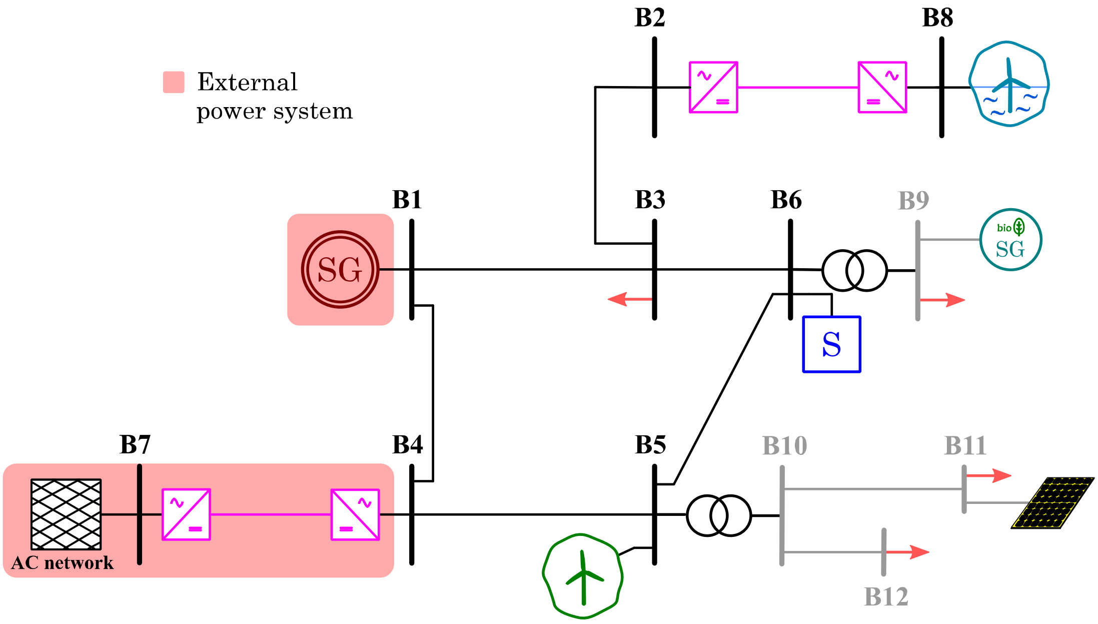


Figure 37. Sketch of scenarios 17-18 (type III)

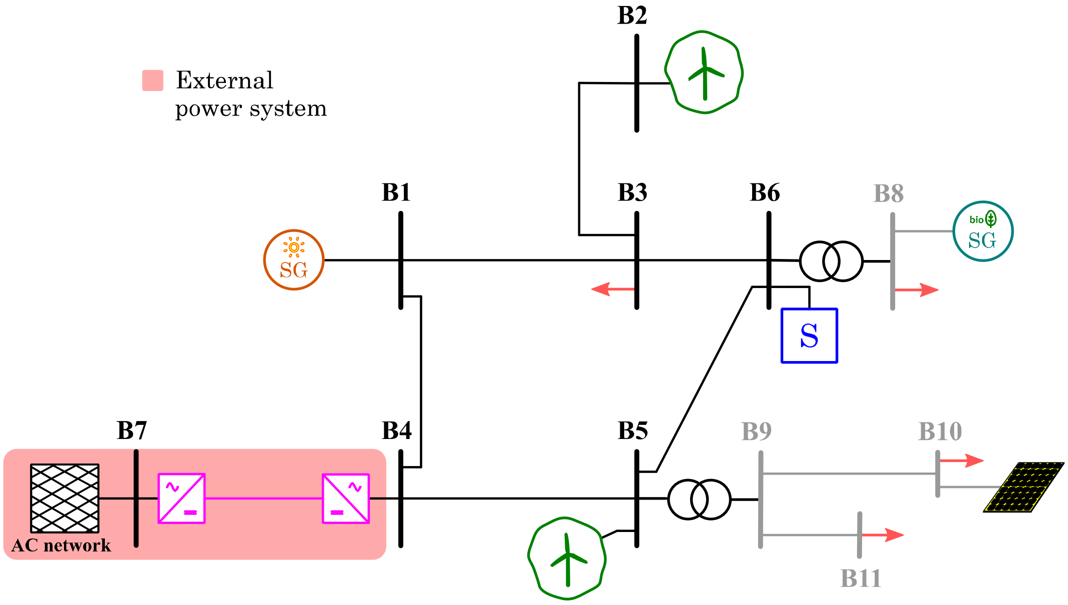


Figure 38. Sketch of scenarios 19-20 (type III)

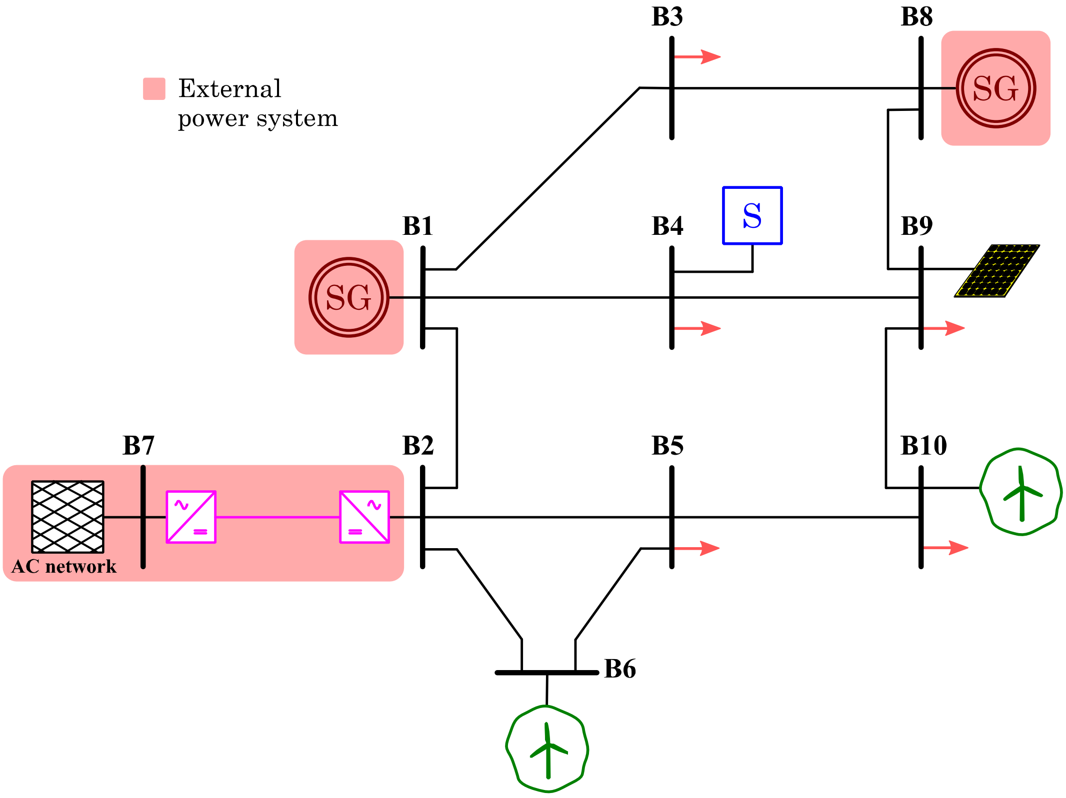


Figure 39. Sketch of scenarios 21-22 (type III)

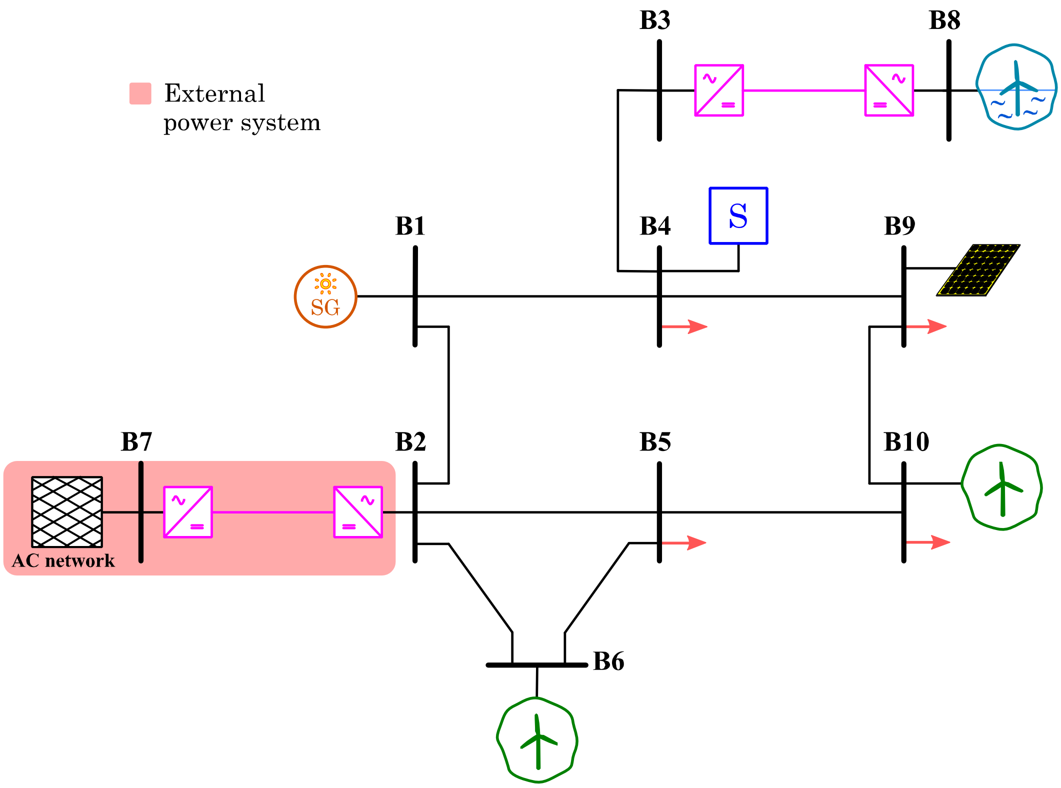


Figure 40. Sketch of scenarios 23-24 (type III)

2.3 Worldwide relevant examples

A detailed search of areas with scenarios that are similar to the preliminary ones presented in the previous section has been conducted. This study aims to identify real locations where the DVPP scenarios that are finally designed in this work package can be inspired on, to some extent. The following criteria has been adopted to select the most relevant scenarios:

- Based on types I, II and III defined before
- Locations restricted to Europe
- Only transmission is considered
- Relevant amount of renewable resources (currently or potentially)
- Ratio of power between the largest and the smallest power plant of around 5 (up to 10 in some cases)

The following legend is used throughout the different case scenarios. In cases where this legend does not apply, a different legend is included in the corresponding case.

* Under construction

** Small WFs and PVPPs grouped by areas so they represent a PP with relevant capacity

*** Small WFs and PVPPs connected directly to distribution (no data of distribution lines length)

**** Small PVPPs or no data

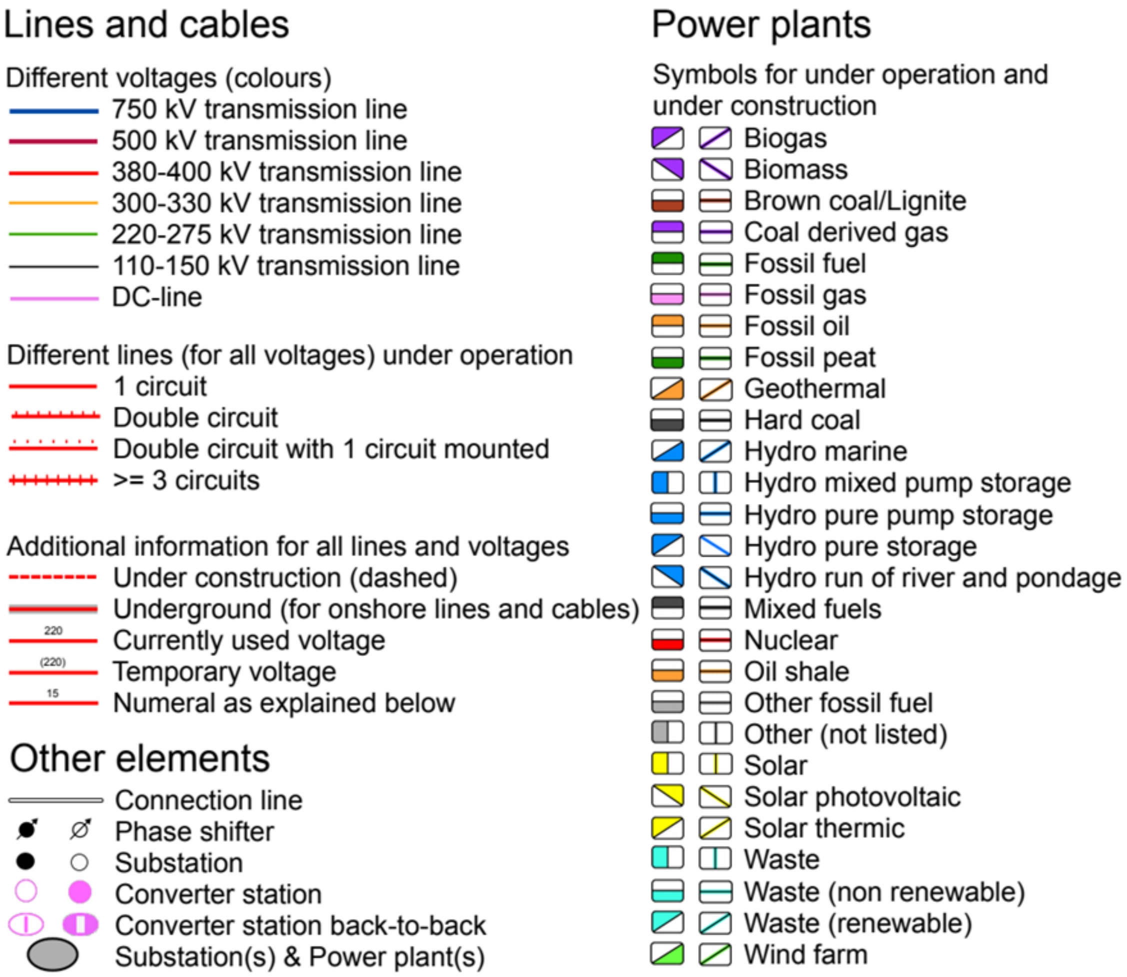


Figure 41. Legend used in the real scenario maps

2.3.1 Type I: Isolated

2.3.1.1 Gran Canaria (Canary Islands) (similar to Scenario 5, 6)

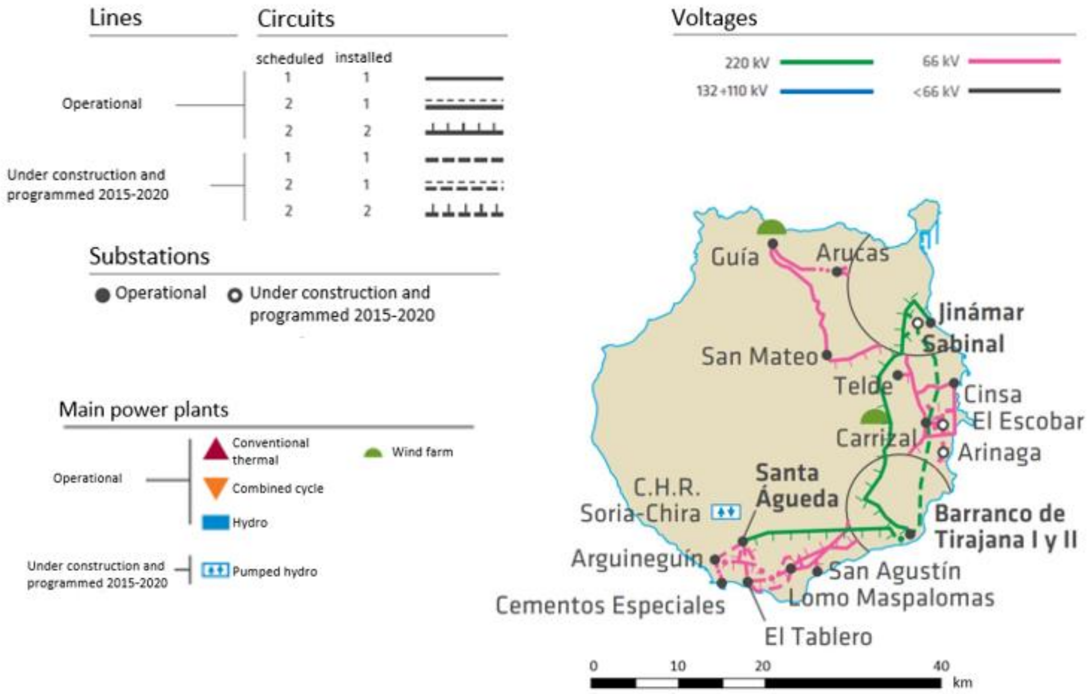


Figure 42. Gran Canaria (Canary Islands) scenario [53]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Jinámar	Gas / Diesel	260	69.4
Barranco de Tirajana I & II	Gas / Diesel	213 + 433	
Soria-Chira*	Hydro pumped	200	15.3
Wind farms**	Wind	157	12.1
▪ San Bartolomé de Tirajana	Wind	58	
▪ Santa Lucía	Wind	42	
▪ Agüimes	Wind	49	
PVPPs**	PV	42	3.2
		1305	

Table 4. Gran Canaria (Canary Islands) scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Jinámar – Barranco de Tirajana	30	220
Barranco de Tirajana – Santa Águeda	25	220
Wind farms – Distribution***	-	20 - 66
PV – Distribution***	-	20 - 66

Table 5. Gran Canaria (Canary Islands) scenario – Summary of transmission lines

2.3.1.2 Tenerife (Canary Islands) (similar to Scenario 6)

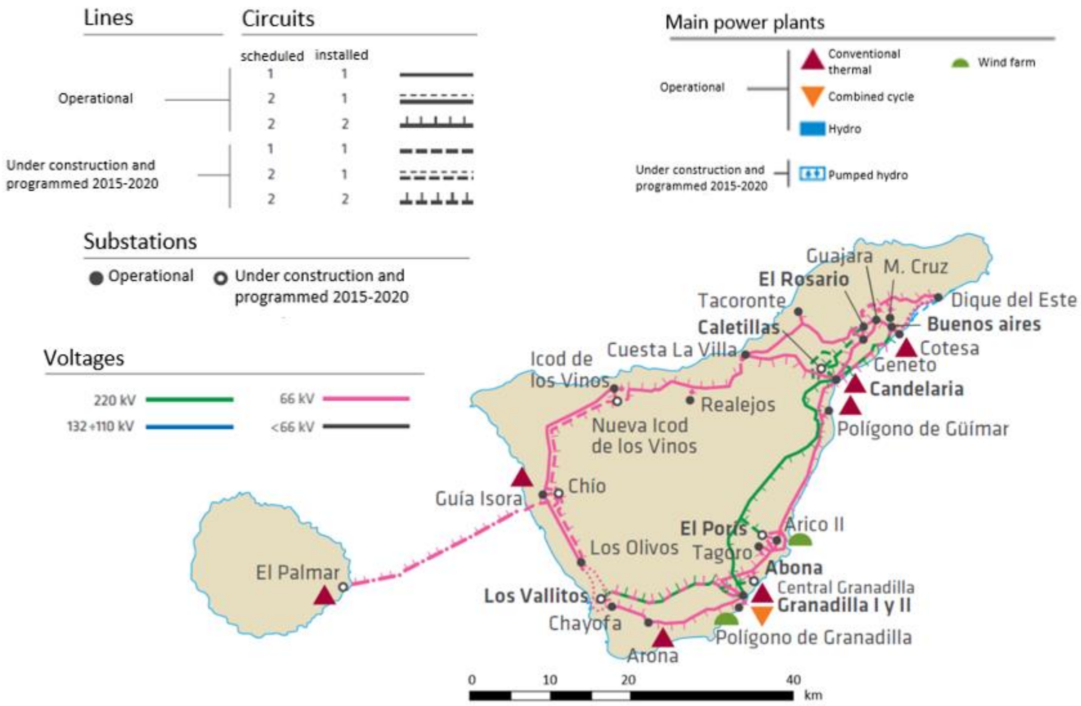


Figure 43. Tenerife (Canary Islands) scenario [53]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Granadilla I & II	Gas/Diesel	432 + 261	53.4
Candelaria	Gas/Fueloil	180	17.2
Guía Isora	Gas/Fueloil	43	
Wind farms**	Wind	187	14.4
- Arico	Wind	98	
- Arico/Fasnia	Wind	21	
- Granadilla de Abona	Wind	66	
PVPPs**	PV	116	8.9
Arona	Gas	43	6.1
Cotesa	Gas	36	
		1298	

Table 6. Tenerife (Canary Islands) scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Candelaria – Granadilla	40	220
Granadilla – Arona	13	66
Wind farms – Distribution***	-	20 - 66
PV – Distribution***	-	20 - 66

Table 7. Tenerife (Canary Islands) scenario – Summary of transmission lines

2.3.1.3 São Miguel (Açores) (similar to Scenario 6)

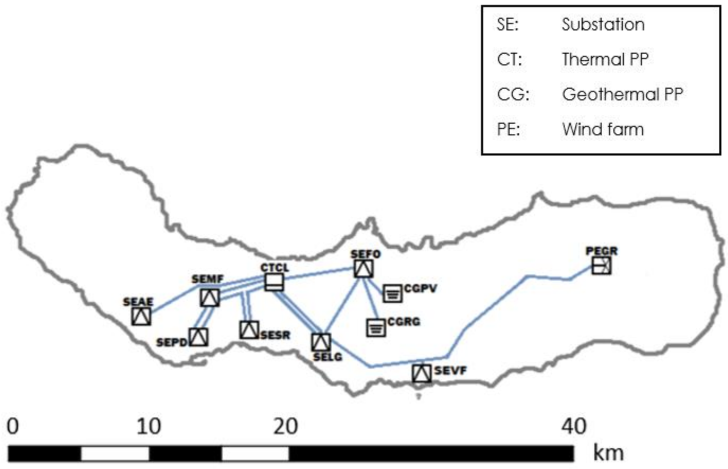


Figure 44. São Miguel (Açores) scenario [54]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Caldeirao	Thermal	67	63.5
Ribeira Grande	Geothermal	16.6	28
Pico Vermelho	Geothermal	13	
Graminhais	Wind	9	8.5
		105.6	

Table 8. São Miguel (Açores) scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
CTCL – SEAE	9.38	60
CTCL – SEMF	5.66	60
CTCL – SESR	3.97	60
CTLC – SEFO	9.85	60
CTLC – SELG	2.06	60
CGPV – SEFO	1.8	30
CGRG – SEFO	4.56	60
PEGR – SEVF	15	60
PEGR – SELG	30.83	60

Table 9. São Miguel (Açores) scenario – Summary of transmission lines

2.3.1.4 Iceland (similar to Scenario 7, 8)

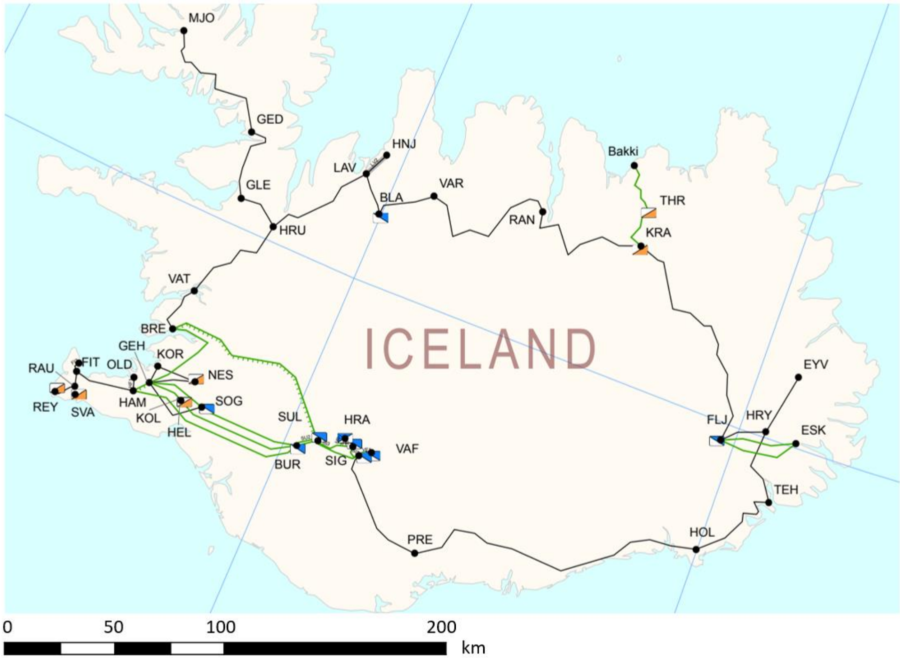


Figure 45. Iceland scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
BUR (Búrfellsstöð)	Hydro	270	63
SUL (Sultartangastöð)	Hydro	120	
SIG (Sigalda)	Hydro	150	
VAF (Vatnsfell)	Hydro	90	
FLJ (Fljotsdalur)	Hydro	690	
BLA (Blanda)	Hydro	150	
REY (Reykjanes)	Geothermal	100	28
SVA (Svartsengi)	Geothermal	75	
HEL (Hellsheidi)	Geothermal	300	
NES (Nesjavellir)	Geothermal	120	
KRA (Krafla)	Geothermal	60	
HRA (Hrauneyjafoss)	Pumped hydro	210	9
		2335	

Table 10. Iceland scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
SIG – HRY	260	132
FLJ – HRY	15	132
FLJ – KRA	5	132
KRA – BLA	130	132
BLA – BRE	120	132
BRE – GEH	30	220
HAM – BUR	75	220
NES – GEH	20	220
REY – HAM	30	132

Table 11. Iceland scenario – Summary of transmission lines

2.3.2 Type II: Synchronously interconnected (AC)

2.3.2.1 Centre-West France (similar to Scenario 13, 15)

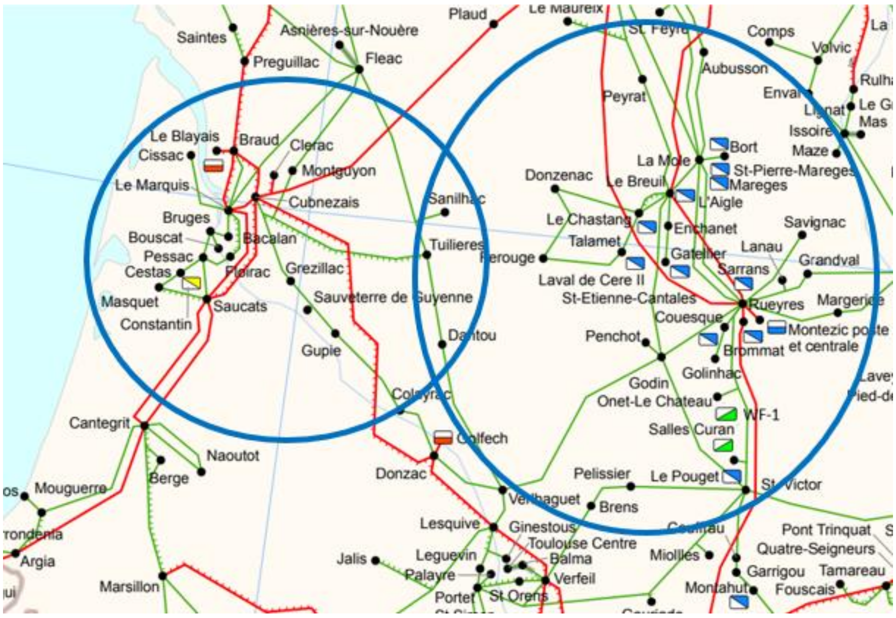


Figure 46. Centre-West France scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Le Blayais	Nuclear	3800	61.9
Golfech	Nuclear	2600	
Bort	Hydro	230	24.5
St-Pierre	Hydro	120	
Mareges	Hydro	144	
L'Aigle	Hydro	349	
Le Chastang	Hydro	293	
Laval de Cere II	Hydro	108	
St-Etienne-Cantales	Hydro	107	
Sarrans	Hydro	183	
Le Pouget	Hydro	446	
Brommat	Hydro	420	
Couesque	Hydro	119	
Montezic	Hydro pumped	910	8.9
Constantin (Cestas)	PV	300	3
Small PVPPs	PV	****	
Wind Farms	Wind	200	1.7
- Salles Curan	Wind	87	
- WF-1	Wind	100	
		10329	

Table 12. Centre-West France scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Le Pouget – Brommat	80	220
L'Aigle – Rueyres	60	400
Montezic – Rueyres	5	400
Bort – La Mole	10	220
La Mole – Breuil	15	220
Cestas – Le Marquis	50	220
Le Blayais – Le Marquis	40	400
Golfech – Le Marquis	200	400, 220
Golfech – Rueyres	180	220

Table 13. Centre-West France scenario – Summary of transmission lines

2.3.2.2 South Portugal (similar to Scenario 13, 14)

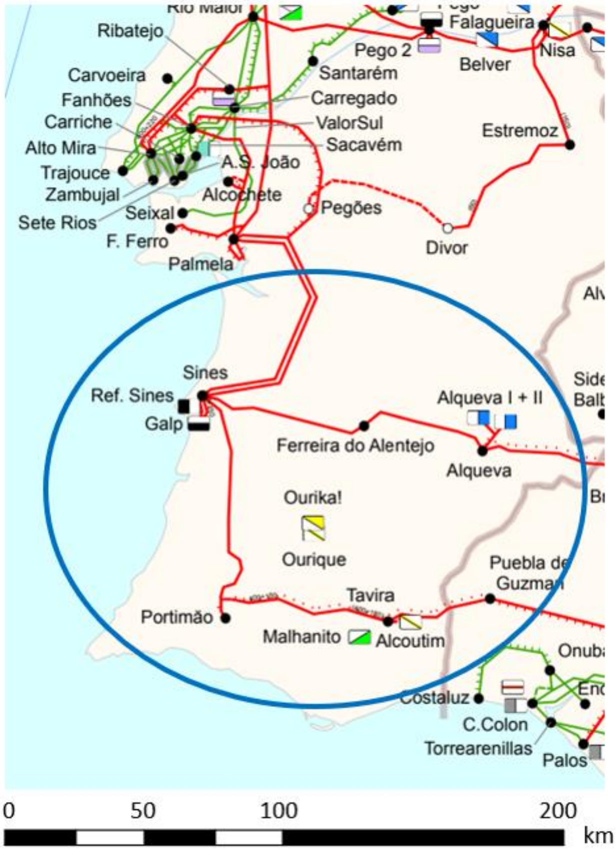


Figure 47. South Portugal scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Ref. Sines	Coal	1250	59,4
Galp	Coal	80	
Alqueva I + II	Hydro pumped	520	23,2
Ourika	PV	50	14,3
Ourique*	PV	50	
Alcoutim*	PV	221	
Malhanito	Wind	67	3
		2238	

Table 14. South Portugal scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Alqueva – Sines	100	400
Sines – Portimao	80	400
Portimao – Tavira	50	400
Malhanito – Tavira	10	-
Alcoutim – Tavira *	5	400

Table 15. South Portugal scenario – Summary of transmission lines

2.3.2.3 South-West Spain (similar to Scenario 15, 16)

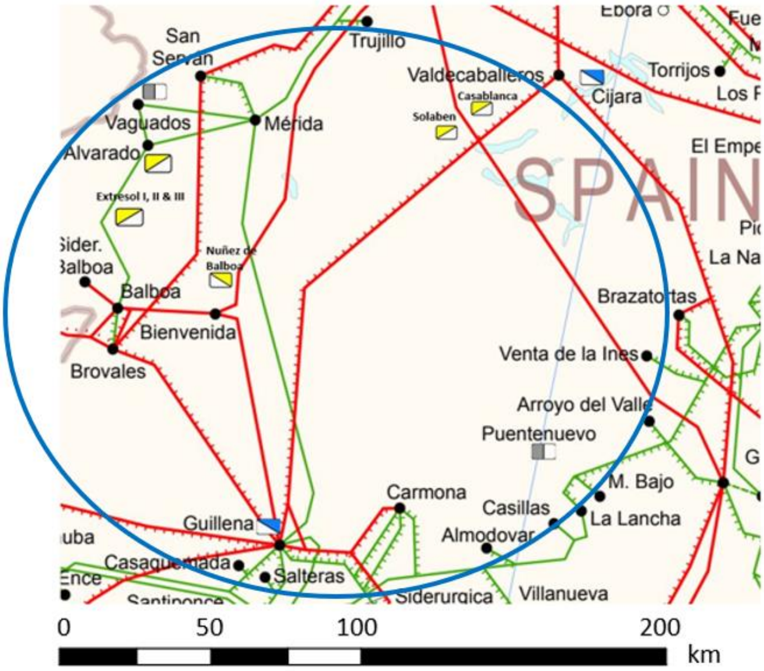


Figure 48. South-West Spain scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Nuñez de Balboa	PV	500	45
Extresol I, II & III	CSP	150	36
Casablanca	CSP	50	
Solaben	CSP	200	
Guillena	Hydro	210	19
Puentenuevo	-	Decomissioned	
		1110	

Table 16. South-West Spain scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Bienvenida – Guillena	80	400
Guillena – Valdecaballeros	150	400
Extresol I, II & III – Alvarado	21.3	66
Casablanca – Valdecaballeros	16.4	132
Solaben – Valdecaballeros	17	400
Nuñez de Balboa - Bienvenida	12.38	400

Table 17. South-West Spain scenario – Summary of transmission lines

2.3.2.4 South Italy (similar to Scenario 13, 14)

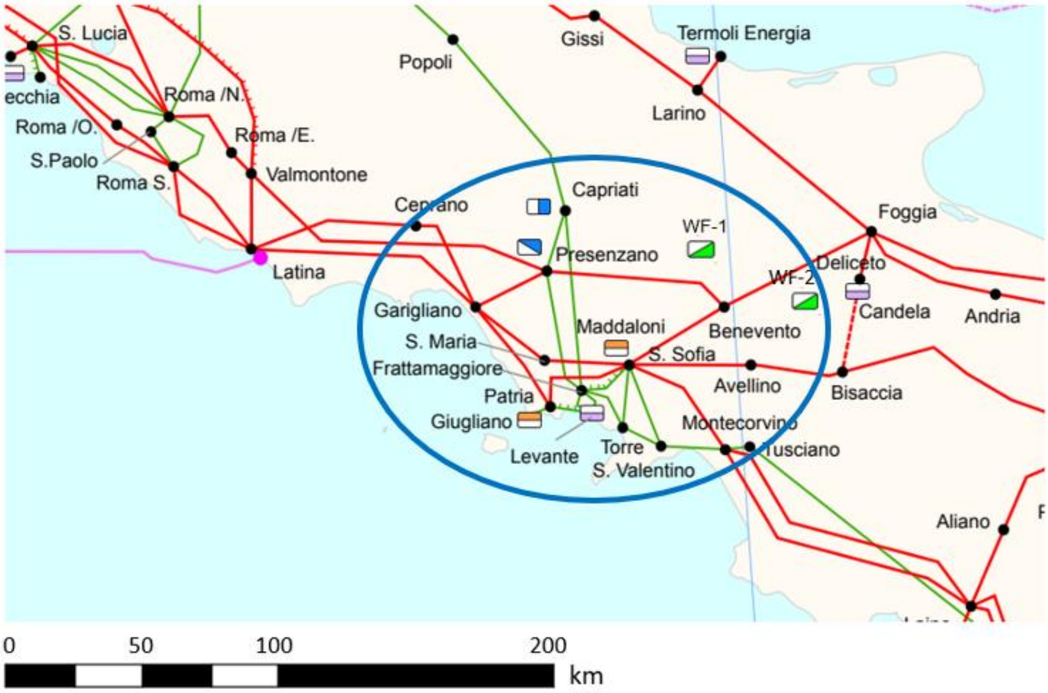


Figure 49. South Italy scenario [55]

Power Plant	**Type**	**Capacity [MW]**	**Power ratio [%]**
Presenzano	Hydro	1000	40.3
Maddaloni	Oil	352	28.3
Giugliano	Oil	352	
WF-1	Wind	120	16.5
WF-2	Wind	290	
Levante	Gas	250	10
Capriati	Hydro pumped	120	4.9
		2484	

Table 18. South Italy scenario – Summary of power plants

Transmission line	**Length [km]**	**Voltage [kV]**
Capriati – Presenzano	20	220
Presenzano – Benevento	60	400
Presenzano – Levante	50	220
WF-1 – Benevento	25	-
WF-2 – Benevento	25	-
Maddaloni – Giugliano	25	400

Table 19. South Italy scenario – Summary of transmission lines

2.3.2.5 Greece (similar to Scenario 14, 16)

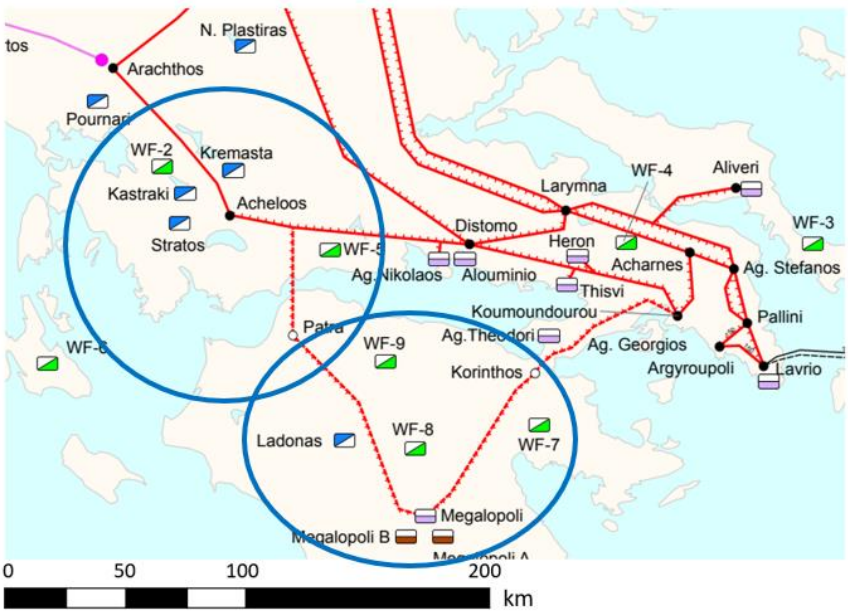


Figure 50. Greece scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Kastraski	Hydro	320	24.7
Stratos	Hydro	157	
Kremasta	Hydro	437	
Pournari	Hydro	300	
N. Plastiras	Hydro	129	
Ladonas	Hydro	70	
Ag. Nikolaos	Gas	432	52.5
Heron	Gas	569	
Ag. Theodori	Gas	433	
Alouminio	Gas	334	
Megalopoli	Gas	811	
Thisvi	Gas	410	
WF-2	Wind	90	18.3
WF-3	Wind	105	
WF-4	Wind	205	
WF-5	Wind	90	
WF-6	Wind	80	
WF-7	Wind	130	
WF-8	Wind	170	
WF-9	Wind	170	
Megalopoli B	Coal	256	4.5
		5698	

Table 20. Greece scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Megalopoli – Patra	100	400
Arachthos – Acheloos	75	400
Acheloos – Distomo	100	400
Megalopoli – Korinthos	90	400
Patra – Acheloos	60	400

Table 21. Greece scenario – Summary of transmission lines

2.3.2.6 Netherlands – North Sea (similar to Scenario 14, 16)

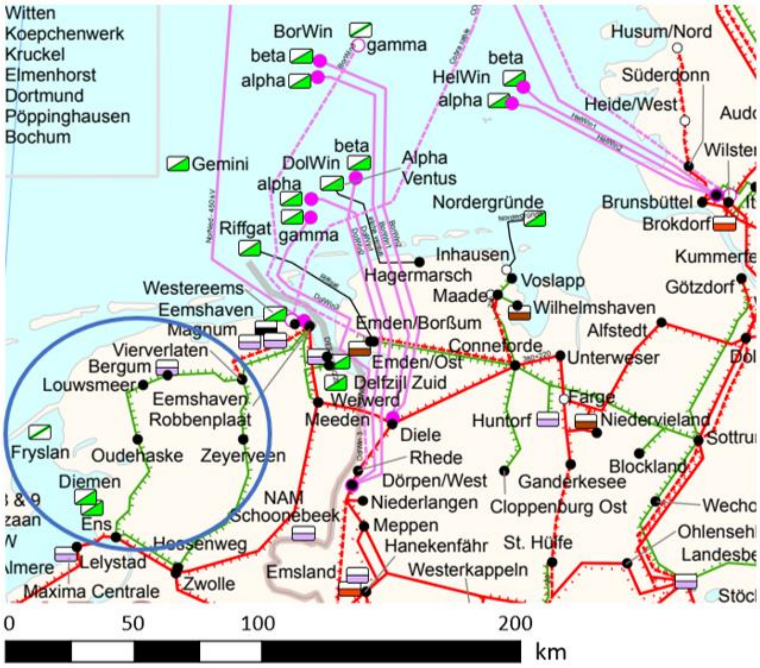


Figure 51. Netherlands – North Sea scenario [55]

Power plants	Type	Capacity [MW]	Power ratio [%]
Fryslan*	Wind	320	52.4
Diemen (Noordoostpolder buitendijks & Noordoostpolder binnendijks)	Wind	126 + 285	
Bergum	Gas	664	47.6
		1395	

Table 22. Netherlands – North Sea scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Ens – Bergum	75	220
Noordoostpolder buitendijks & Noordoostpolder binnendijks	15	110
Bergum – Vierverlaten	30	220

Table 23. Netherlands – North Sea scenario – Summary of transmission lines

2.3.2.7 North-West Denmark (similar to Scenario 15, 16)

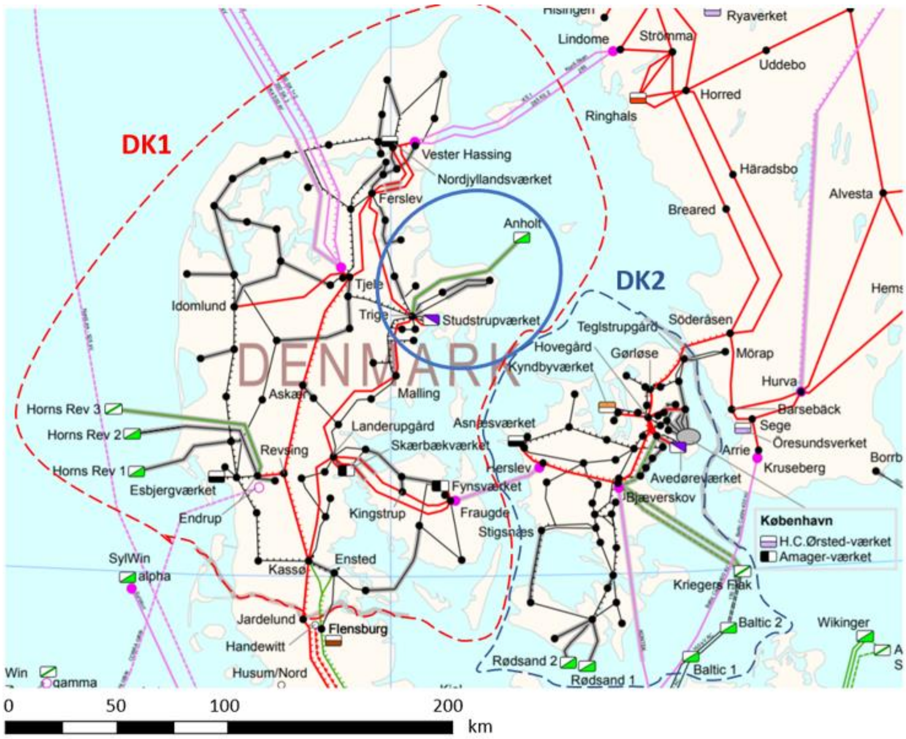


Figure 52. North-West Denmark scenario [55]

Note that areas of operation DK1 and DK2 are indicated in red and blue dashed lines.

Power Plant	Type	Capacity [MW]	Power ratio [%]
Anholt Havmollepark	Wind	400	36.7
Studstrupvaerket	Biomass	700	63.3
		1100	

Table 24. North-West Denmark scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Anholt Havmollepark – Trige	84.3	220
Studstrupvaerket – Trige	13.2	2x150; 1x400

Table 25. North-West Denmark scenario – Summary of transmission lines

2.3.2.8 North Wales (similar to Scenario 13, 15)

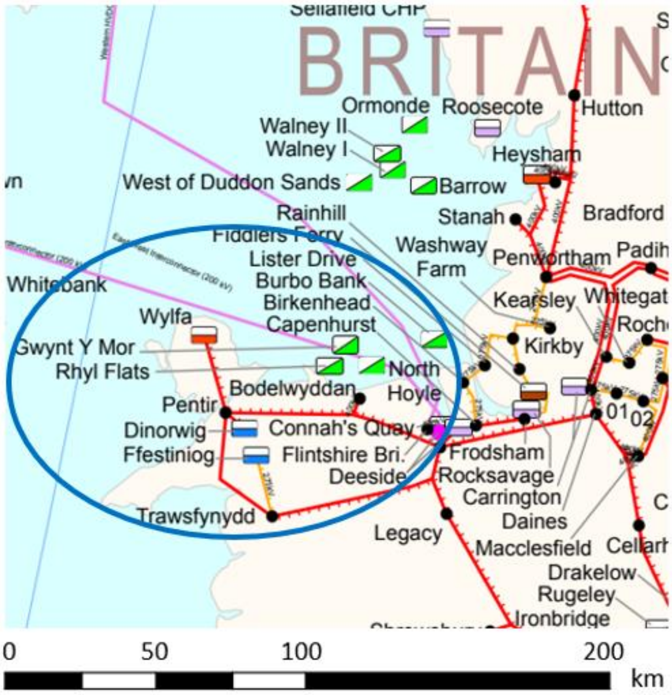


Figure 53. North Wales scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Dinorwig	Hydro pumped	1800	42.3
Ffestiniog	Hydro pumped	360	
Connah Quay	Gas	1380	36.7
Deeside	Gas	498	
Rhyl Flats	Wind	90	21
Gwynt Y Mor	Wind	576	
North Hoyle	Wind	60	
Burbo Bank	Wind	348	
Wylfa	-	Decomissioned	
		5112	

Table 26. North Wales scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Rhyl Flats – Bodelwyddan	20	132
Gwynt Y Mor – Bodelwyddan	25	132
Burbo Bank – Bodelwyddan	30	220
Dinorwig – Pentir	5	400
Ffestiniog – Trawsfynydd	15	275
Pentir – Bodelwyddan	80	400
Bodelwyddan – Deeside (substation)	40	400

Table 27. North Wales scenario – Summary of transmission lines

2.3.2.9 West Denmark (similar to Scenario 13, 14)

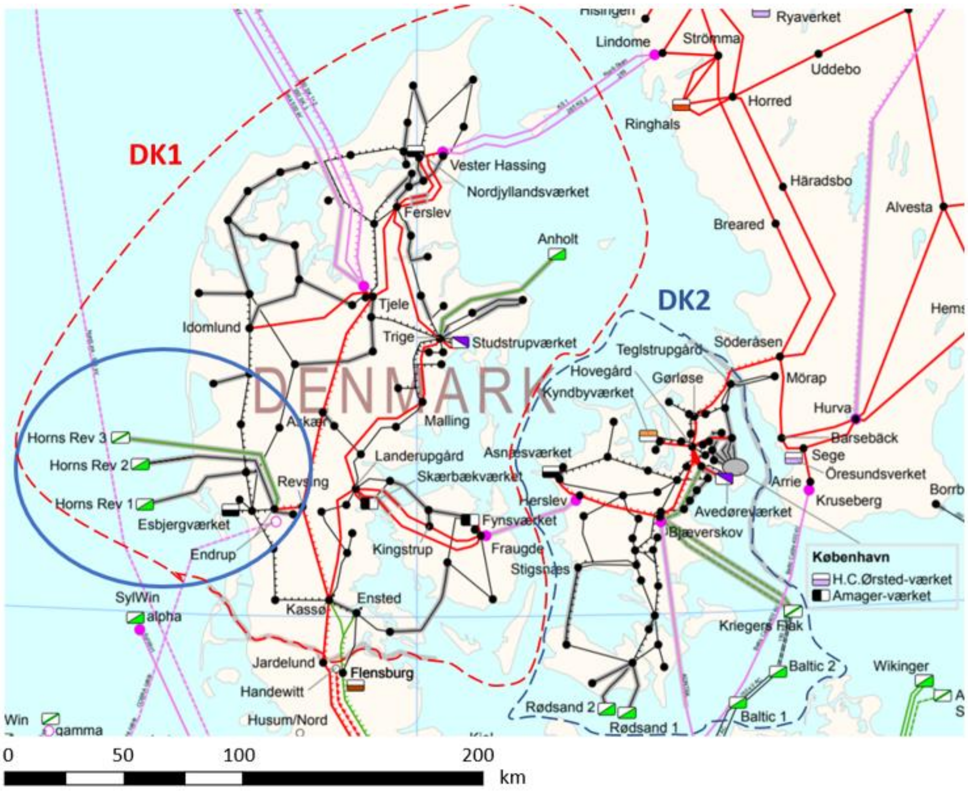


Figure 54. West Denmark scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Horns Rev 3	Wind	400	66.7
Horns Rev 2	Wind	209	
Horns Rev 1	Wind	160	
Esbjergvaerket	Coal	383	33.3
		1152	

Table 28. West Denmark scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Horns Rev 3 - Endrup	80	220
Horns Rev 2 - Endrup	98	150
Horns Rev 1 - Karlsgarde	56	150
Esbjergvaerket - Endrup	10	150
Endrup (DK) – Eemshaven (NL)	325	320 (and 700MW)

Table 29. West Denmark scenario – Summary of transmission lines

2.3.2.10 South Norway (similar to Scenario 15, 16)

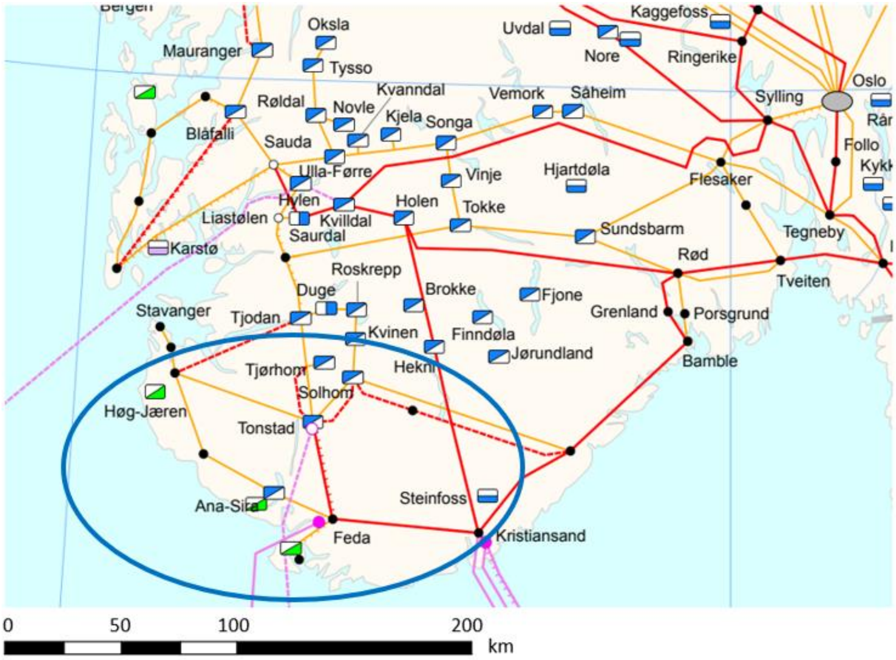


Figure 55. South Norway scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Jaeren	Hydro	74	77.5
Ana-Sira	Hydro	150	
Tjodan	Hydro	110	
Tjorhom	Hydro	120	
Solhom	Hydro	200	
Tonstad	Hydro	960	
Duge	Hydro pumped	200	14.8
Steinfoss	Hydro pumped	109	
Ana-Sira	Wind	160	7.7
		2083	

Table 30. South Norway scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Hog-Jaeren – Ana-Sira	75	300
Ana-Sira - Feda	25	300
Tonstad – Feda	40	420
Feda – Deutschland DC link	580	450 (cap. 700 MW)
Feda – Kristiansand	60	420
Kristiansad – Denmark DC link	240	SK1 & 2 250 SK3 350 SK4 500 (cap. 1700 MW)

Table 31. South Norway scenario – Summary of transmission lines

2.3.2.11 North Sea (similar to Scenario 15, 16)

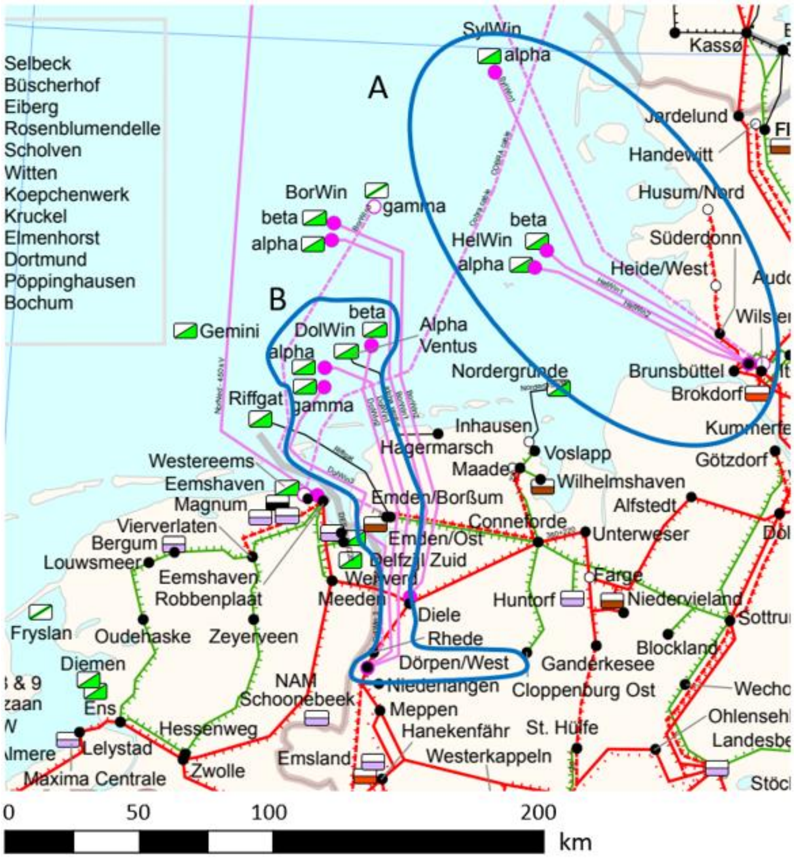


Figure 56. North Sea scenario (A and B) [55]

A. 100% wind

Converter station	Capacity [MW]	Offshore wind farms connected	Capacity [MW]
HelWin Alpha	576	Nordsee Ost	295
		Meerwind Süd	288
HelWin Beta	690	Amrumbank West	288
SylWin Alpha	864	Sandbank	288
		DanTysk	288
		WindPark Butendiek	288

Table 32. North Sea scenario (A) – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
HelWin Alpha – Büttel	130	320
HelWin Beta – Büttel	130	320
SylWin Alpha – Büttel	205	320

Table 33. North Sea scenario (A) – Summary of transmission lines

B. 100% wind

Converter station	Capacity [MW]	Offshore wind farms connected	Capacity [MW]
DolWin alpha	800	Trianel Windpark Borkum *	200
		Merkur-Offshore	396
DolWin beta	916	Gode Wind I	330
		Gode Wind II	252
		Nordsee One	332
DolWin gamma	900	Borkum Riffgrund 2	448
		Merkur-Offshore	396

Table 34. North Sea scenario (B) – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
DolWin alpha	165	320
DolWin beta	135	320
DolWin gamma	160	600

Table 35. North Sea scenario (B) – Summary of transmission lines

2.3.3 Type III: Non-synchronously interconnected (HVDC)

2.3.3.1 Balearic Islands (similar to Scenario 21, 22)

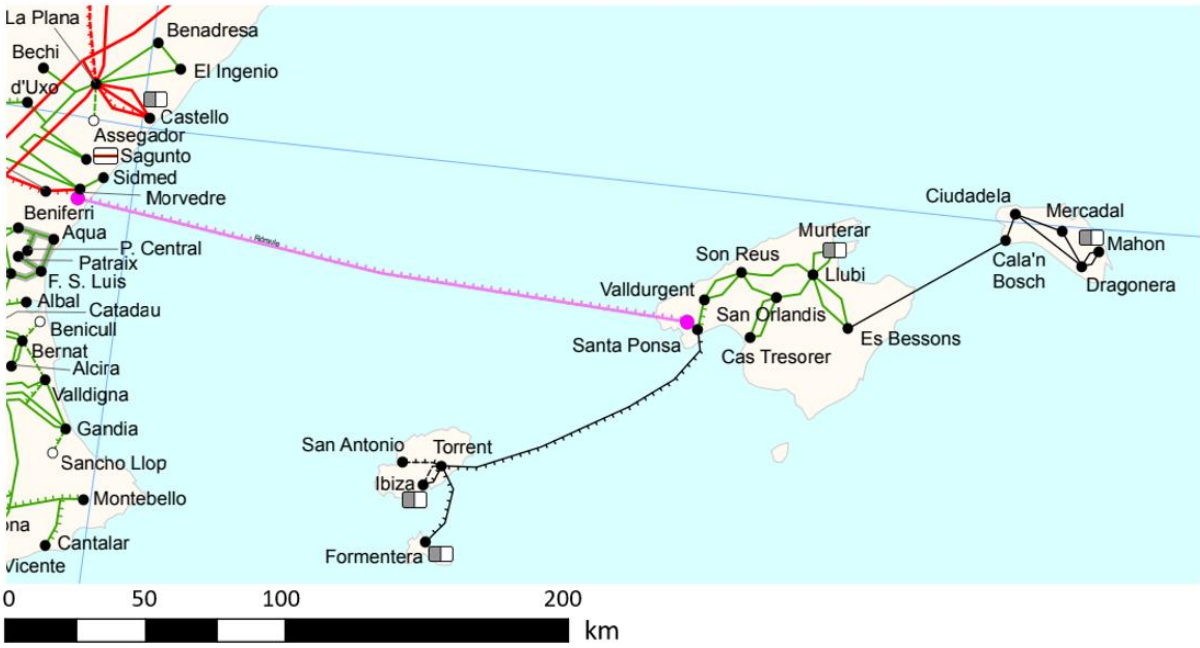


Figure 57. Balearic Islands scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Murterar	Gas/Coal	510	34.8
Cas Tresorer	Gas	480	32.8
Son Reus	Gas/Diesel	218	32.4
Mahon	Gas/Diesel	76	
Ibiza	Gas/Diesel	180	
		1464	

Table 36. Balearic Islands scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Santa Ponse – Morvedre	200	250

Table 37. Balearic Islands scenario – Summary of transmission lines

2.3.3.2 Corsica and Sardinia (similar to Scenario 21, 22)

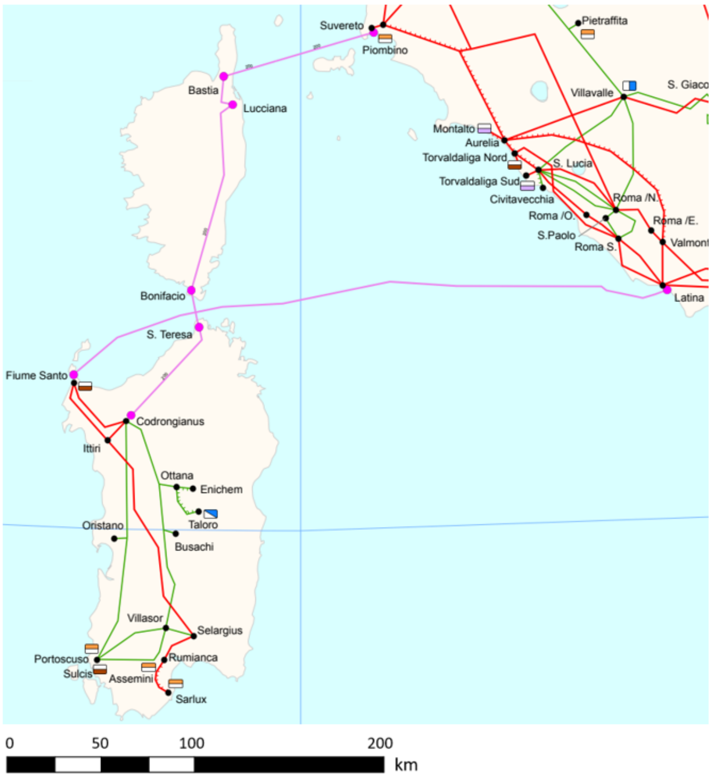


Figure 58. Corsica and Sardinia scenario [55]

Power Plant	Type	Capacity [MW]	Power ratio [%]
Sarlux	Oil	690	56.6
Portoscuso	Oil	388	
Assemini	Oil	200	
Sulcis	Coal	611	27
Taloro	Wind	369	16.4
		2258	

Table 38. Corsica and Sardinia scenario – Summary of power plants

Transmission line	Length [km]	Voltage [kV]
Suvereto – Lucciana – Condrongianus	385	200
Latina – Flume Santo	435	500

Table 39. Corsica and Sardinia scenario – Summary of transmission lines

2.4 Selection of realistic scenarios

Based on the different types of scenarios and the additional characteristics considered in Section 2.2, together with the real scenarios identified in Section 2.3, a preliminary selection is presented.

These scenarios are still preliminary, in the sense that the power ratings of the transmission lines and the generation units are not defined. Based on these layouts, the specific rating of each element will be given by the algorithm described later on in Section 3, based on the different inputs and restrictions considered.

Four final scenarios have been considered, based on the following:

- At least one scenario of each type (I, II and III) is selected
- A tentative grid layout is considered for each type, based on the already existing scenarios in Europe, considering around 10 buses.
    - Type I: islanded scenarios are in general smaller and simpler as compared to continental scenarios. Therefore, a smaller number of buses (in this case, 7) and a single voltage level is considered for this case (Figure 59).
    - Type II: the vast majority of scenarios are AC interconnected systems, and they are typically bigger and more meshed. Therefore, a higher number of buses (in this case, 13) and different voltage levels (i.e. transmission and distribution) are considered. Moreover, two different versions of this type of scenario are considered. One corresponds to a typical southern Europe scenario (Figure 60), whereas the other corresponds to a typical northern Europe scenario (Figure 61), including HVDC interconnected offshore wind.
    - Type III: regarding HVDC interconnected scenarios without AC interconnections, they typically correspond to bigger islands. For that reason, the grid layout considered is slightly more complex, with a higher number of buses as compared to Type I (in this case, 11). Also, different voltage levels are also considered in this case (Figure 62).

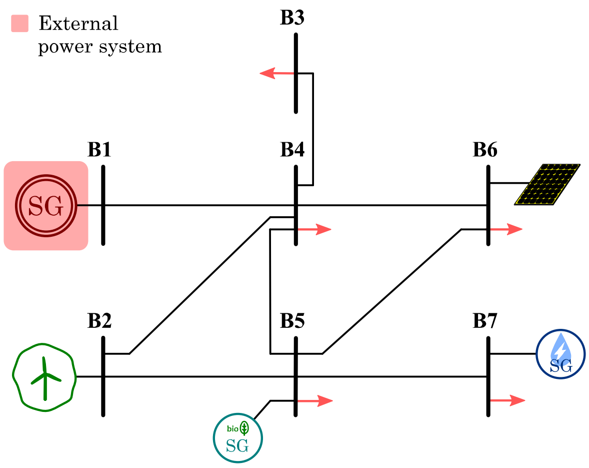


Figure 59. Selected scenario 1: type I

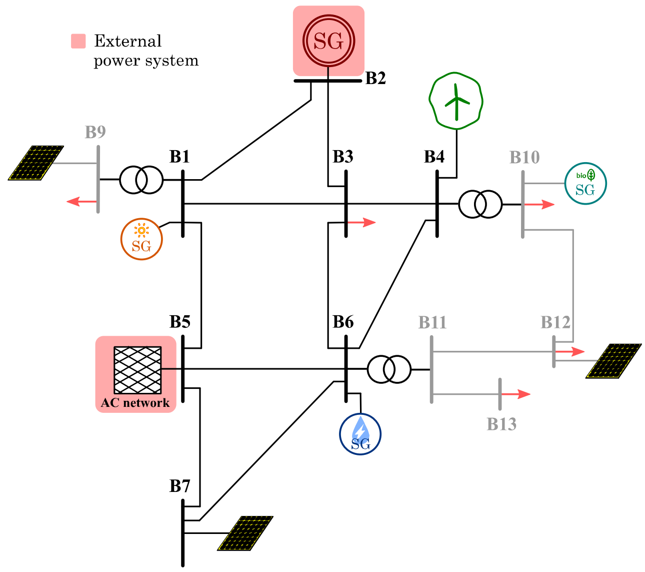


Figure 60. Selected scenario 2: AC interconnected (type II, southern Europe)

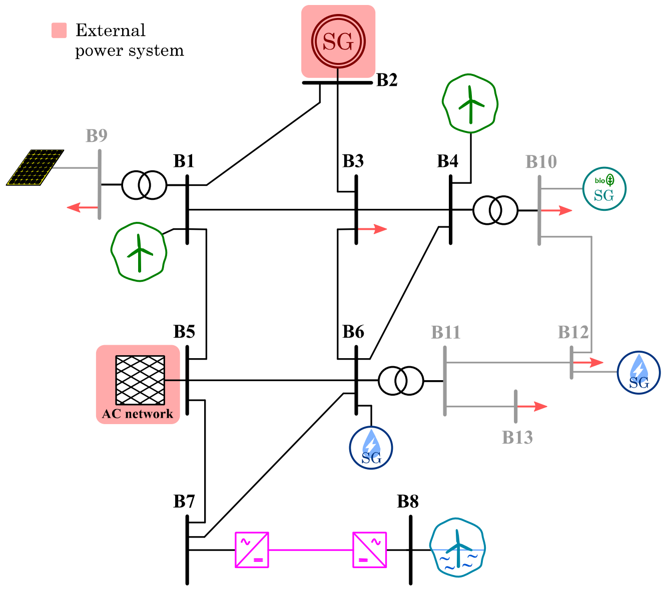


Figure 61. Selected scenario 3: AC interconnected (type II, northern Europe)

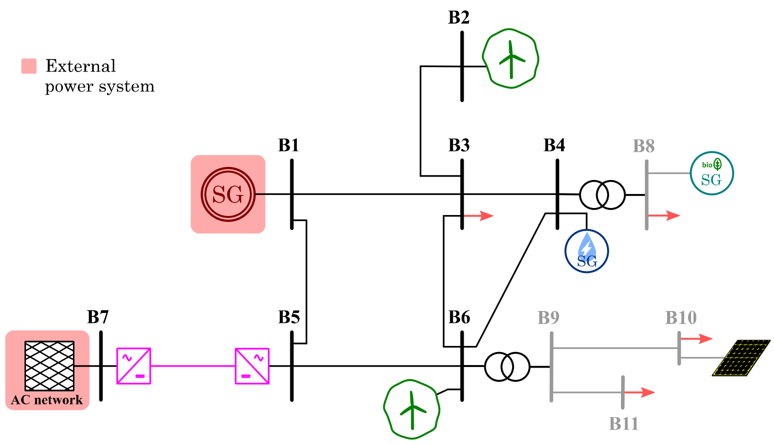


Figure 62. Selected scenario 4: DC interconnected (type III)

3 Detailed definition and sizing of the scenarios

In this section, a methodology to size the renewable generation for the realistic scenarios selected in Section 2.4 is described. The objective is to quantify the elements that are included in the previous scenarios, such as the rated capacity of the power plants or the capacity and length of the transmission lines. This requires the choice of a specific location in order to define the system demand and the resource availability. This quantification will be applied considering different situations, such as current situation, Future 2030 and Future 2050, resulting in different levels of renewable penetration.

The sizing methodology is based on an optimization of the generation costs, considering the European or the local policies about the objectives of renewable generation. The grid restrictions are not considered in the optimization algorithm. The optimization quantifies the renewable generation that should be installed to fulfill the minimum share of renewable generation, while minimizing the total generation cost.

3.1 Generation cost optimization

An optimization algorithm has been developed in Python in order to obtain the renewable capacity that minimizes the generation costs. A flowchart of this algorithm is shown in Figure 63. Several inputs are required in order to define the power plants and system characteristics. In particular, the following inputs are needed for the different elements considered:

- **Conventional generation**: it is assumed to be already installed in the system, so CAPEX is not considered. Then, the inputs required for the conventional thermal power plants are the installed capacity and the operational expenses, which includes the fuel cost.
- **Renewable generation**: in order to define the renewable installed capacity, the optimization algorithm needs as inputs both the capital and the operational expenses. In addition, the availability of associated resources, e.g. irradiation for PV or wind speed for wind, is also required. If a renewable power plant has already been built, the CAPEX is no longer needed, yet the installed capacity is.
- **System**: the system is defined through two parameters: the total demand at each time interval and the minimum share of renewable generation.

The previous inputs will be specifically defined for each conventional and renewable generation model.

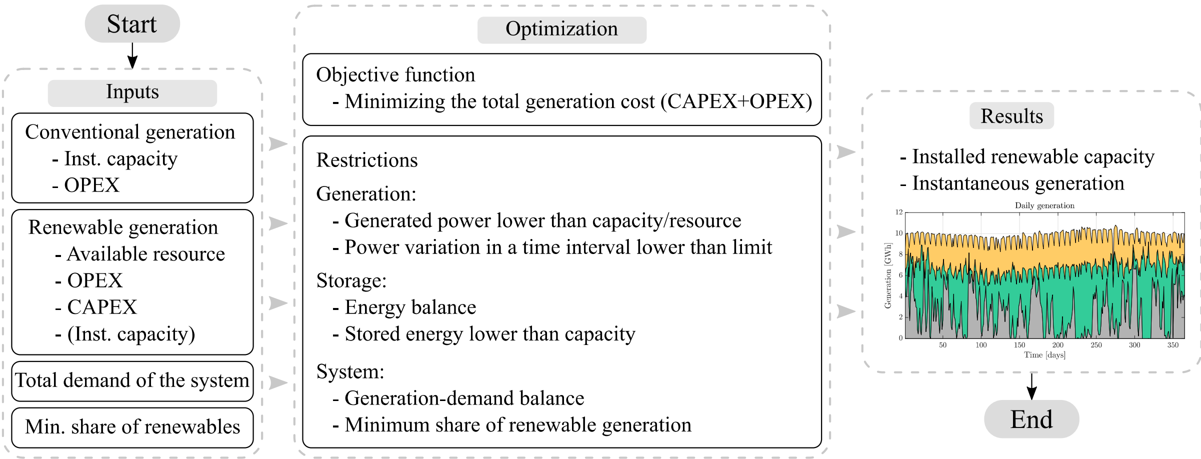


Figure 63. Overview of the optimization algorithm

3.1.1 Modelling of the system elements

Models for the conventional and renewable generation have been implemented in Python in order to represent the particular characteristics of every energy resource. Four models have been considered: conventional power plants, renewable power plants without storage (PV and wind), solar thermal power plants and pure pumping hydro power plants. System restrictions are also included in the model.

3.1.1.1 Conventional power plants

Conventional power plants, e.g. coal or gas-based power plants, are assumed to be already installed in the system, considering only its operational costs during its lifetime. The conventional power plants are represented by the following restrictions:

1. ***Maximum power generation:*** the instantaneous power generation must be lower or equal to the installed capacity of the power plant.

$$x_{GCi,t} \leq G_{Ci} \qquad \forall i, \forall t \tag{1}$$

   where i denotes each of the C_i conventional power plants, $x_{GCi,t}$ is the instantaneous generation of the conventional power plant C_i at the time t and G_{Ci} is the installed capacity of the conventional power plant C_i.

2. ***Maximum power variation between two consecutive time intervals:*** this restriction limits the power variation of the conventional power plants, considering the dispatchability of the different technologies. For instance, gas power plants are much faster than nuclear power plants. Then, this restriction is defined as follows:

$$\left| x_{GCi,t+1} - x_{GCi,t} \right| \leq \Delta G_{Ci} \qquad \forall i, \forall t \in [1, T-1] \tag{2}$$

   where ΔG_{Ci} is the maximum power variation of the conventional power plant C_i between two intervals and T is the last time interval considered in the optimization.

3.1.1.2 Renewable generation without storage (PV and wind)

Modeling of PV and wind power plants is very similar to conventional power plants, as they present the same two restrictions. However, in this case, the maximum generation will depend on the availability of the resource. The two restrictions for the renewable generation are written as:

1. ***Maximum power generation:*** the renewable generation depends not only on the installed capacity of the power plant, but also on the availability of the resource:

$$x_{GRj,t} \leq G_{Rj} \cdot C_{Rj} \qquad \forall j, \forall t \tag{3}$$

where j refers to each of the R_j renewable power plants, $x_{GRj,t}$ is the instantaneous generation of the renewable power plant R_j at the time t, G_{Rj} is the installed capacity of the renewable power plant R_j and C_{Rj} is the available resource expressed in pu. The solar and wind resources can be obtained for a specific location and time interval in [56].

2. ***Maximum power variation between two consecutive time intervals:*** for the purpose of the present study, this restriction limits the power variation of the renewable power plants on an hourly basis.

$$\left| x_{GRj,t+1} - x_{GRj,t} \right| \leq \Delta G_{Rj} \qquad \forall j, \forall t \in [1, T-1] \tag{4}$$

where ΔG_{Rj} is the maximum power variation of the renewable power plant R_j.

3.1.1.3 Pure pumping hydro power plants

The hydro power plants have been considered as pure pumping plants without external contributions of water. Then, the energy stored only depends on the pumping and turbine power balance. The pumping hydro power plants have been modelled as follows:

1. ***Maximum power generation/consumption:*** in this case, both the pumping and the turbine power must be lower than the installed capacity. The same nominal power has been considered for both senses of the power.

$$x_{GHk,t} \leq G_{Hk} \qquad \forall k, \forall t \tag{5}$$

$$x_{PHk,t} \leq G_{Hk} \qquad \forall k, \forall t \tag{6}$$

where k refers to each of the H_k hydro power plants, $x_{GHk,t}$ and $x_{PHk,t}$ are the instantaneous generation and pumping power of the hydro power plant H_k at the time t, respectively, and G_{Hk} is the installed capacity of the hydro power plant H_k.

2. ***Maximum power variation between two consecutive time intervals:*** this restriction is applied to the turbine and pumping power:

$$\left|x_{GHk,t+1} - x_{GHk,t}\right| \leq \Delta G_{Hk} \qquad \forall k, \forall t \, \epsilon \, [1, T-1] \tag{7}$$

$$\left|x_{PHk,t+1} - x_{PHk,t}\right| \leq \Delta G_{Hk} \qquad \forall k, \forall t \, \epsilon \, [1, T-1] \tag{8}$$

where ΔG_{Hk} is the maximum power variation of the hydro power plant H_k.

3. ***Energy balance of the storage system:*** the energy stored depends on the energy balance between the pumping and turbine powers.

$$x_{Sk,t+1} = x_{Sk,t} + x_{PHk,t} \cdot \eta_P - \frac{x_{GHk,t}}{\eta_G} \qquad \forall k, \forall t \, \epsilon \, [1, T-1] \tag{9}$$

where $x_{Sk,t}$ is the energy stored in the hydro power plant H_k at the time t and η_P and η_T are the pumping and turbine efficiencies, respectively.

4. ***Maximum energy storage:*** the maximum energy storage is defined by the capacity of the upper reservoir of the hydro power plant.

$$x_{Sk,t} \leq S_{Hk} \qquad \forall k, \forall t \tag{10}$$

Where S_{Hk} is the storage capacity of the hydro power plant H_k.

3.1.1.4 Solar thermal power plants

The solar thermal power generation represented in this study is based on parabolic troughs, as it is the main technology used in the solar thermal power plants [57]. These power plants are usually equipped with thermal storage systems, which are sized to have the capability to maintain rated power for several hours. Then, the solar thermal generation has been represented including the thermal power absorbed by the parabolic troughs, the thermal storage and the electric generation:

1. ***Maximum thermal power absorbed by the solar field:*** the thermal power absorbed by the parabolic troughs highly depends on the solar irradiation and the angle of incidence ***[58]***:

$$x_{TSl,t} \leq i_{Sl,t} \cdot r_l \cdot G_{Sl} \cdot \eta_{O,l} \cdot \eta_{Ef} \cdot K(\theta) \cdot \cos\theta \qquad \forall l, \forall t \tag{11}$$

where l refers to each of the S_l solar thermal power plants, $x_{TSl,t}$ is the thermal power absorbed by the S_l solar thermal power plant at time t, $i_{Sl,t}$ is the direct normal solar irradiation in kW/m^2, r_l is a ratio which relates the solar field surface needed to generate 1 kWe (electric power kW) (see [58]), G_{Sl} is the rated electrical power of the plant, $\eta_{O,l}$ is the peak optical efficiency, η_{Ef} is an efficiency factor which considers other losses, such as thermal, cleanliness or tracking losses, and $K(\theta)$ is a factor obtained from the angle of incidence (incidence angle modifier). $K(\theta)$ can be calculated as [59]:

$$K(\theta) = 1 - \frac{7 \cdot 10^{-4} \cdot \theta + 36 \cdot 10^{-6} \cdot \theta^2}{\cos\theta} \tag{12}$$

where θ is the angle of incidence, in degrees, which can be found for a specific location and time in [60].

2. ***Maximum electric power:*** the maximum electric power is restricted by the rated power of the solar thermal power plant:

$$x_{GSl,t} \leq G_{Sl} \qquad \forall l, \forall t \tag{13}$$

where $x_{GSl,t}$ is the electric power generation of the solar thermal power plant S_l at the time t.

3. ***Maximum power variation between two consecutive time intervals:*** this restriction is only applied to the electric power:

$$\left|x_{GSl,t+1} - x_{GSl,t}\right| \leq \Delta G_{Sl} \qquad \forall l, \forall t \in [1, T-1] \tag{14}$$

where ΔG_{Sl} is the maximum electric power variation of the solar thermal power plant S_l.

4. ***Energy balance of the thermal storage system:*** the thermal energy stored varies based on the thermal and electric powers as:

$$x_{Sl,t+1} = x_{Sl,t} + x_{TSl,t} - \frac{x_{GSl,t}}{\eta_{th,l}} \qquad \forall l, \forall t \in [1, T-1] \tag{15}$$

where $x_{Sl,t}$ is the energy stored in the solar thermal power plant S_l at the time t and η_{th} is the thermoelectric efficiency of the thermal power plant. An ideal storage system has been assumed, so storage losses are not considered.

5. ***Maximum thermal energy storage:*** the maximum thermal energy is defined by the capacity of the storage tank:

$$x_{Sl,t} \leq S_{Sl} \qquad \forall l, \forall t \tag{16}$$

where S_{Sl} is the storage capacity of the solar thermal power plant S_l.

3.1.1.5 Power system

The power system has been modelled using and aggregated representation, which only considers the total system demand. The grid equations are not included in the model. Then, two restrictions have been implemented:

1. ***Generation-demand balance:*** the power generation must meet the total system demand for every time interval.

$$\sum_{i=1}^{I} x_{GCi,t} + \sum_{j=1}^{J} x_{GRj,t} + \sum_{k=1}^{K} x_{GHk,t} + \sum_{l=1}^{L} x_{GSl,t} = D_t + \sum_{k=1}^{K} x_{PHk,t} \tag{17}$$

where I is the number of conventional power plants, J is the number of PV and wind power plants, K is the number of pumping hydro power plants and L is the number of solar thermal power plants.

2. ***Minimum contribution of renewable generation:*** the minimum share of renewable generation during a year considered by the European or local policies has been included as a restriction as:

$$\sum_{t=1}^{T}\left(\sum_{j=1}^{J} x_{GRj,t} + \sum_{l=1}^{L} x_{GSl,t}\right) >= \alpha \sum_{t=1}^{T} D_t \tag{18}$$

where α is the minimum share of renewable generation expressed in pu. Pumping hydro generation is not included as renewable generation, as its net energy contribution is null or even negative if the pumping and turbine efficiencies are considered.

3.1.2 Optimization problem

The optimization algorithm provides the generation mix that minimizes the cost for the system. In particular, its output is the installed capacity for every renewable generation type as well as the generation mix for every time interval. Then, the objective function of the optimization function can be defined as:

$$\begin{gathered} f_{obj}(x) = OPEX_{Conv}(x) + CAPEX_{Ren}(x) + OPEX_{Ren}(x) \\ \text{subject to } \begin{matrix} h_m(x) = 0, & m \,\epsilon\, [1, M] \\ g_n(x) \leq 0, & m \,\epsilon\, [1, N] \end{matrix} \end{gathered} \tag{19}$$

where x is the variable vector, $f_{obj}(x)$ is the objective function, $OPEX_{Conv}(x)$ is the operation cost of the conventional power plants, $CAPEX_{Ren}(x)$ is the capital cost of the renewable generation that must be installed, $OPEX_{Ren}(x)$ is the operation cost of the renewable generation, $h_m(x)$ are the equality constraints and $g_n(x)$ are the inequality constraints.

The variable vector x includes the instantaneous generation for every time interval for all the generation types considered, as well as the installed capacity of the renewable generation. Then, the variable vector can be defined as:

$$x = [x_C, C_R, x_R, C_H, x_H, C_S, x_S] \tag{20}$$

where

$$x_C = [x_{GCi,1}, \dots, x_{GCi,T}] \quad \forall i \tag{21}$$

$$C_R = [C_{R1}, \dots, C_{RJ}] \tag{22}$$

$$x_R = [x_{GRj,1}, \dots, x_{GRj,T}] \quad \forall j \tag{23}$$

$$C_H = [C_{H1}, \dots, C_{HK}] \tag{24}$$

$$x_H = [x_{GHk,1}, \dots, x_{GHk,T}, x_{PHk,1}, \dots, x_{PHk,T}] \quad \forall k \tag{25}$$

$$C_S = [C_{S1}, \dots, C_{SL}] \tag{26}$$

$$x_S = [x_{GSl,1}, \dots, x_{GSl,T}] \quad \forall l \tag{27}$$

The cost functions are defined as:

$$OPEX_{Conv}(x) = \sum_{t=1}^{T} \left(\sum_{i=1}^{I} x_{GCi,t} \cdot OPEX_{Ci} \right) \tag{28}$$

$$CAPEX_{Ren}(x) = \sum_{j=1}^{J} C_{Rj} \cdot CAPEX_{Rj} + \sum_{k=1}^{k} C_{Hk} \cdot CAPEX_{Hk} + \sum_{l=1}^{L} C_{Sl} \cdot CAPEX_{Sl} \tag{29}$$

$$OPEX_{Ren}(x) = \sum_{t=1}^{T} \left(\sum_{j=1}^{J} x_{Rj} \cdot OPEX_{Rj} + \sum_{k=1}^{K} x_{Hk} \cdot OPEX_{Hk} + \sum_{l=1}^{L} s_{Sl} \cdot OPEX_{Sl} \right) \tag{30}$$

The equality and inequality constraints, $h_m(x)$ and $g_n(x)$, are based on the models of the different generation types described in Section 3.1.1.

3.2 Application of the methodology to the selected scenarios

The previous methodology has been applied to some of the realistic scenarios shown in Section 2.4. Then, two cases have been selected in order to validate the methodology and exemplify the sizing of such scenarios:

- Scenario 1: Type I – Isolated: island
- Scenario 3: Type II – Synchronously interconnected (AC): northern Europe

3.2.1 Scenario 1: Type I – Island

Scenario 1 corresponds to an isolated system (Type I), as described in Section 2.4. Tenerife has been chosen among the locations presented in Section 2.3.1 in order to obtain the system demand and the availability of the solar and wind resources. The hourly power demand of Tenerife varied from 300 to 550 MW approximately in 2019. Hourly data for the whole year can be downloaded from [61].

It has been assumed that a 600-MW coal-fired generation is already installed. Regarding the renewable resources, two possible cases have been considered for this scenario:

- ***Case 1 - without storage:*** the first case does not consider any kind of storage. Then, only PV and wind generations have been included as renewable power plants.
- ***Case 2 - with storage:*** in addition to PV and wind sources, solar thermal generation with storage has been introduced into the system.

The installed capacity of all the renewable technologies has been set as optimization variables. Comparing the results of both cases, it has been analyzed how the energy storage impact on the sizing of the renewable resources.

3.2.1.1 Case 1 – without storage

Initially for this Case 1, the optimization has been executed to obtain the installed capacity and the generation mix for a particular minimum share of renewables (α). It has been set to 74%, which is the objective established by the Spanish government for 2030 [62]. To fulfill this requirement, the optimization algorithm has determined that the wind generation supplies the 43% of the total demand, while the PV provides the 31%, as shown in Figure 64. The installed capacity of the wind and PV generation must be 785 MW and 596 MW respectively, as shown in Figure 64. The relevant demand numbers of this scenario are the following:

- Maximum demand: 552 MW
- Average demand: 405 MW
- Minimum demand: 13 MW (due to a fault)

Figure 65 shows the daily and monthly generation mix for 2019. It can be observed that the PV generation is very similar during the whole year, while the energy provided by the wind generation varies considerably. The coal power plant compensates for the power variation of the wind generation. July and August present the highest contribution of wind energy, while the maximum coal-based generation is found in January and October.

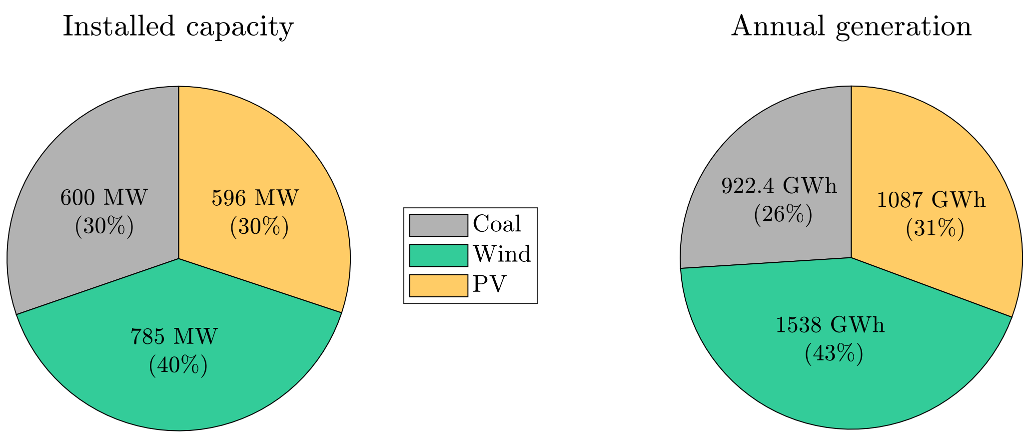
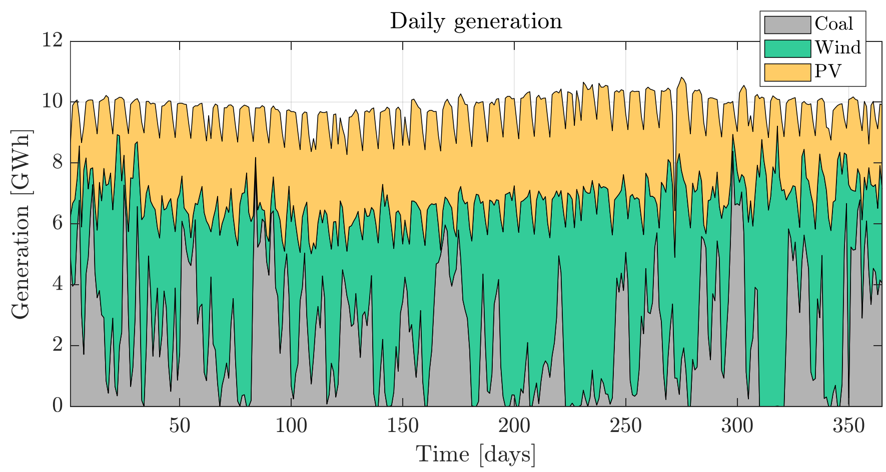
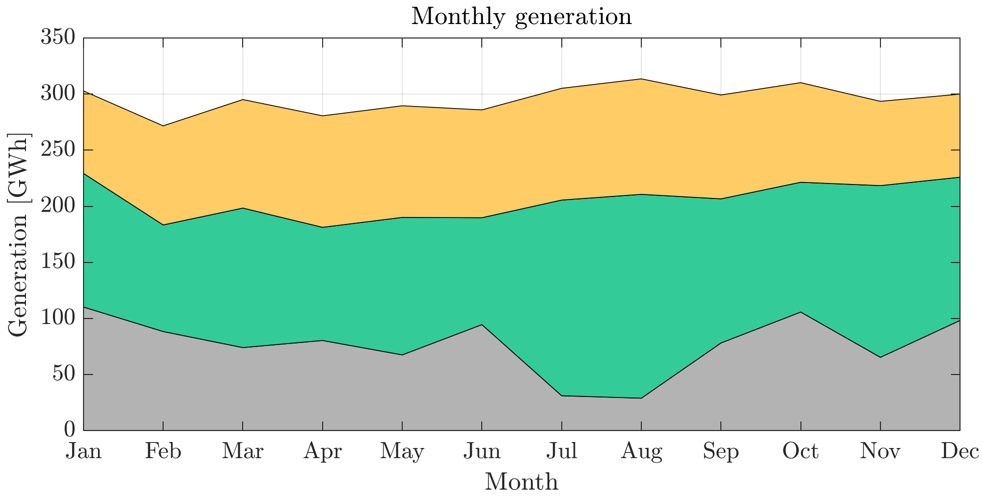


Figure 64. Installed capacity and annual generation mix for Case 1 and $\alpha = 74\%$



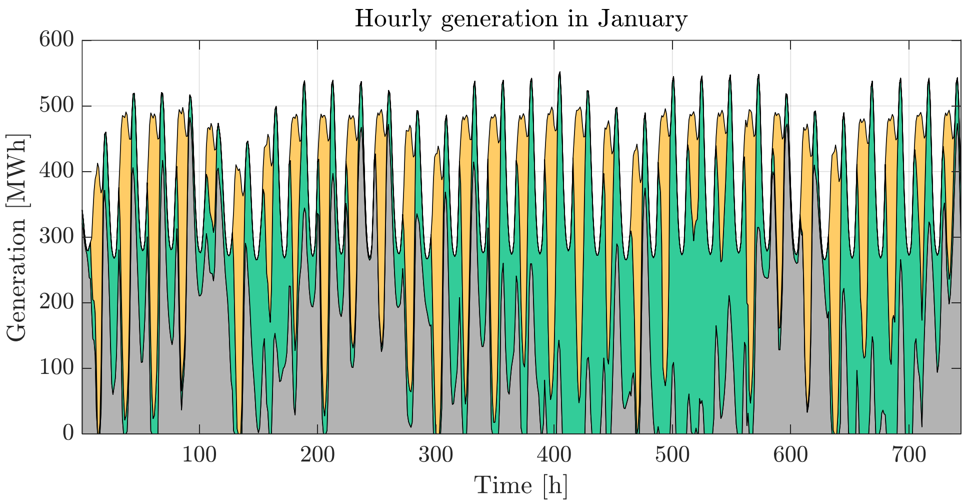
(a)



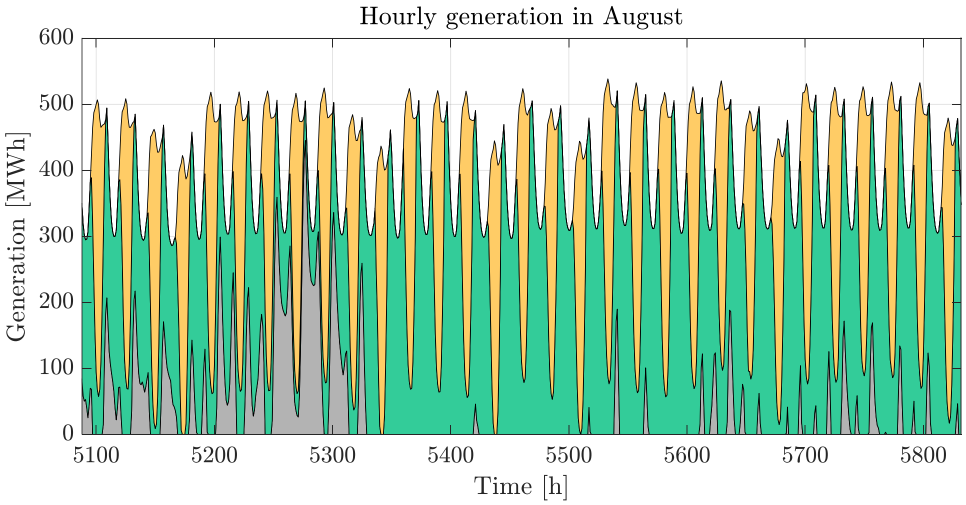
(b)

Figure 65. Generation mix for Case 1 in 2019: (a) daily; (b) monthly

Figure 66 illustrates the hourly generation during January and August. It can be observed the difference between wind and coal contributions. While the presence of coal generation in August is reduced to some days, in January it is required most of the time in order to supply the total demand.



(a)



(b)

Figure 66. Hourly generation for Case 1 during: (a) January; (b) August

In addition, the effect of the minimum share of renewables (α) over the installed capacity of the renewable technologies has also been analyzed. In particular, α has been modified from 0% to 99% in different intervals, obtaining the wind and PV installed capacities shown in Figure 67. It can be observed the exponential curve, requiring an extremely high installed capacity for α close to 100%. This is caused by the lack of solar and wind resources at some time, for example low wind at night, forcing the algorithm to oversize them. For α = 100%, no solution is found as neither PV nor wind generation can supply the demand.

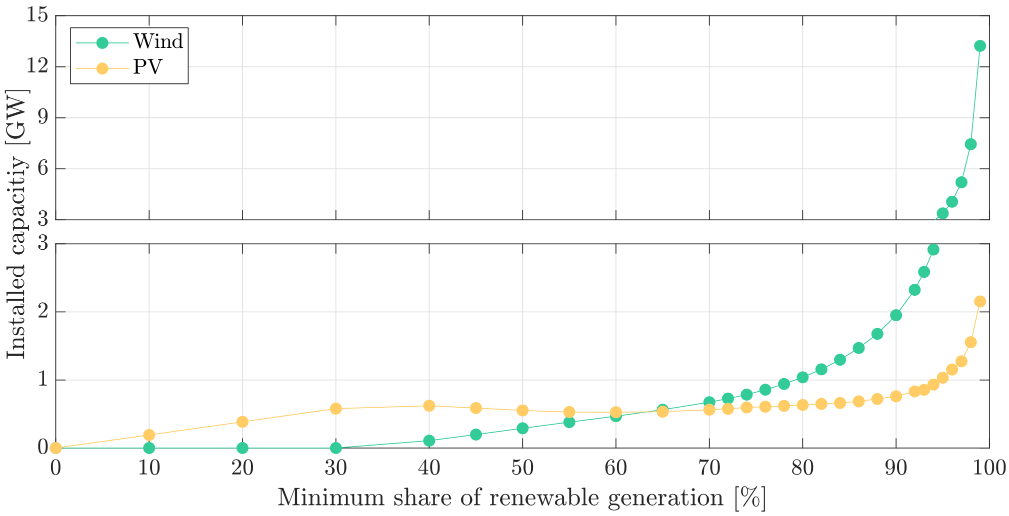


Figure 67. Installed capacity of wind and PV generation for Case 1 and α = 0 to 99%

Based on the results obtained, and on the preliminary layout from Section 2.4, the final scenario is depicted in Figure 68. The scenario contains a total amount of 7 transmission busses and no distribution. The voltage levels of the transmission lines could be, for instance, in the range of 66-220 kV. The obtained capacity for wind and PV is distributed in the different available busses, and two conventional generation units are considered. Different portions of the demand are distributed among some of the buses, and others are left without consumption. The distances are relatively short, as the idea behind this scenario is a relatively small island.

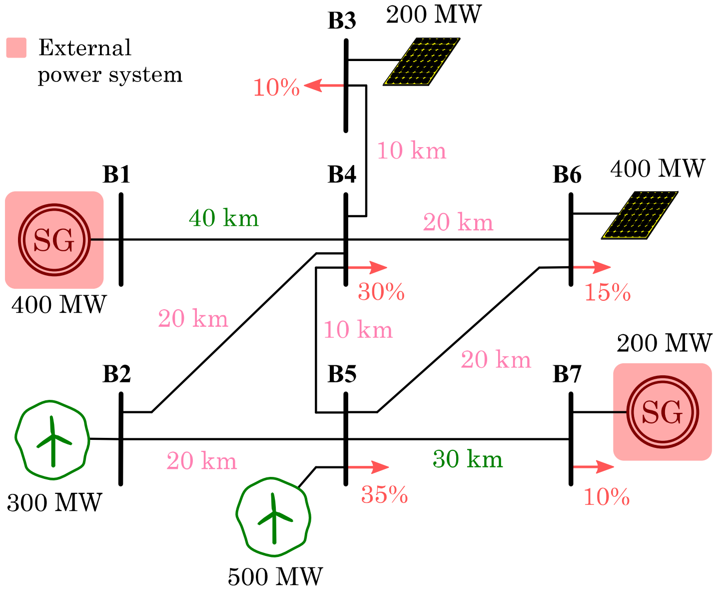


Figure 68. Scenario 1: Island without storage capability – Final proposed layout

3.2.1.2 Case 2 – with storage

To overcome the previous oversizing issue, storage elements can be introduced into the system. In this case, solar thermal power generation has been included in the optimization problem. A thermal storage system equivalent to 7.5 h of rated electric power has been assumed. The actual storage capacity will depend on the rated power of the solar thermal generation, which is also a variable of the optimization problem.

Then, a similar analysis has been carried out to study the renewable generation that must be installed for different α, resulting in Figure 69. Due to the higher cost of the solar thermal generation, the algorithm does not include it in the solution until $\alpha \geq 78.11$ %. Then, for α lower than 78.11 %, Figure 69 is identical to Figure 67. For α above this value, the introduction of solar thermal generation helps the system, avoiding the oversizing of the wind and PV generation. However, for a 100% of renewable penetration the optimization provides a non-realistic solution, as it requires more than 30 GW of wind energy to supply a system with a peak demand around 550 MW (this singularity is not represented in Figure 69). For α = 99.9%, the solution obtained is still acceptable, despite the required renewable capacity is considerably higher than those obtained for 99%. Figure 70 shows the generation cost comparison between Cases 1 and 2. The introduction of storage into the system allows a considerable cost reduction for α higher than 90%.

A specific case when α = 90% has been selected in order to exemplify the performance of the system when the solar thermal power plant is included. Figure 71 shows the installed capacity and the annual generation for every technology. It can be observed how renewables can supply 90% of the energy while their contribution to the installed capacity is only 75%. This is possible thanks to the storage system of the solar thermal power plant. To exemplify the operation of this technology, the electric power, thermal power and thermal energy storage have been depicted during three days in Figure 72.

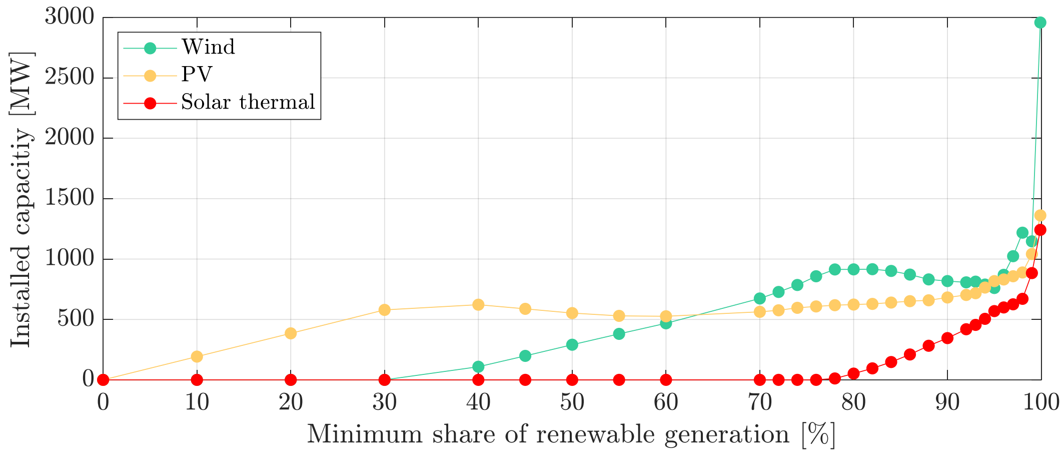


Figure 69. Installed capacity of wind, PV and solar thermal generation for Case 2 and α = 0 to 99.9%

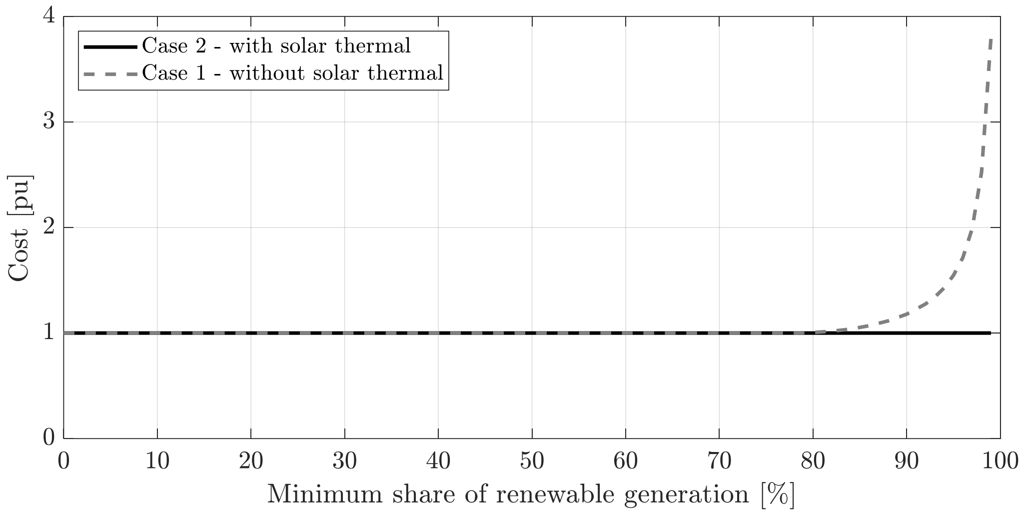


Figure 70. Total generation cost considering Case 2 as the base case

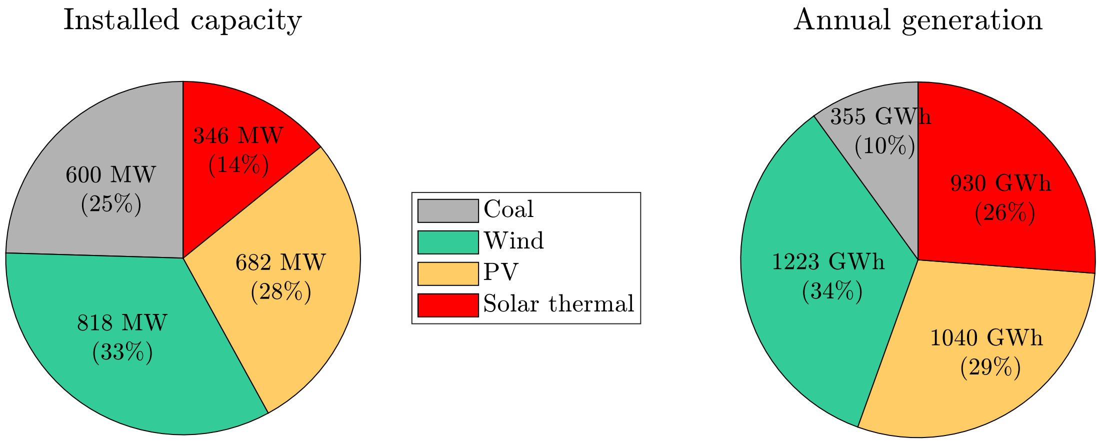


Figure 71. Installed capacity and annual generation mix for Case 2 and $\alpha = 90\%$

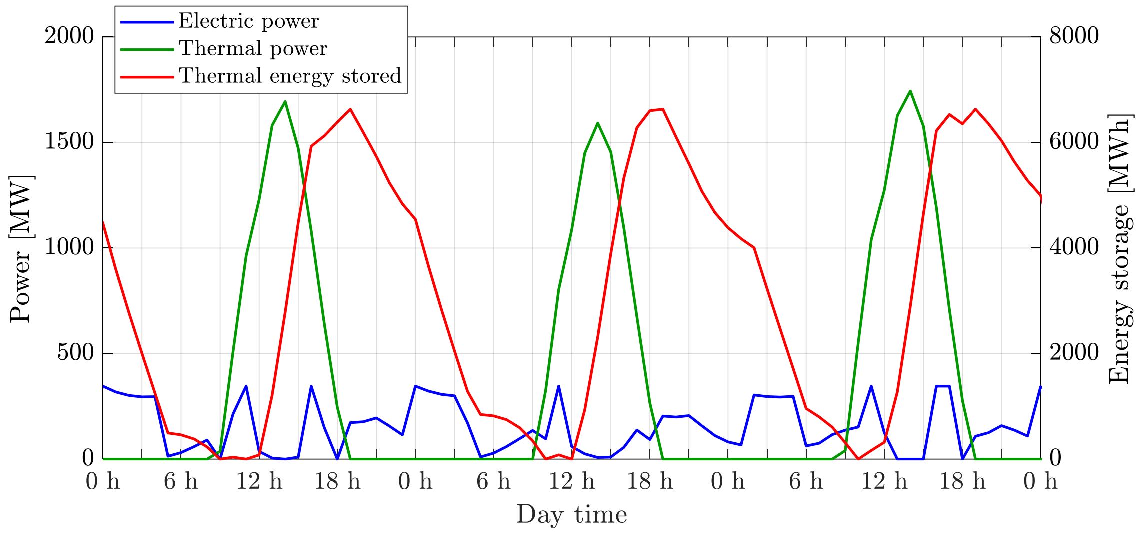
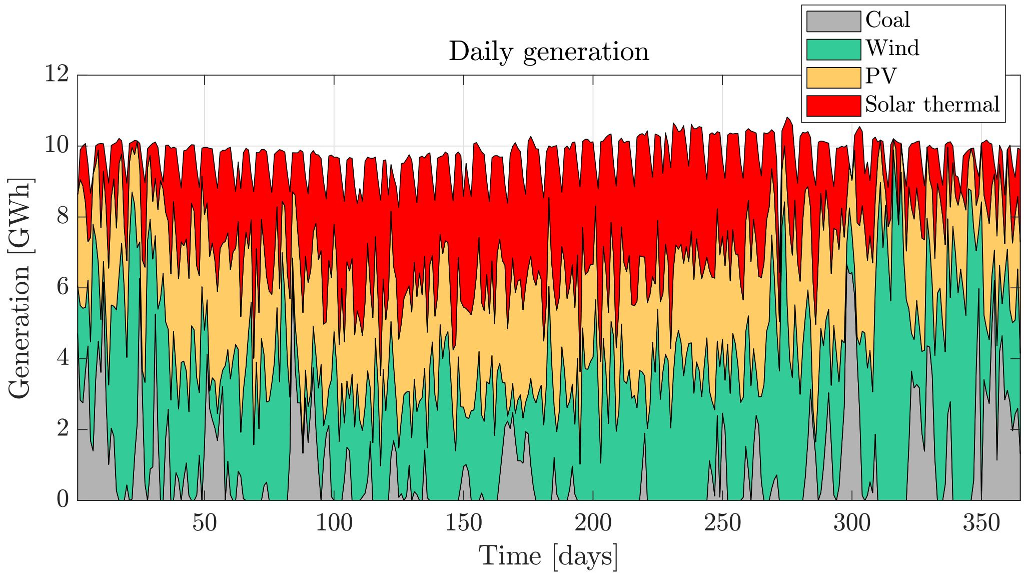
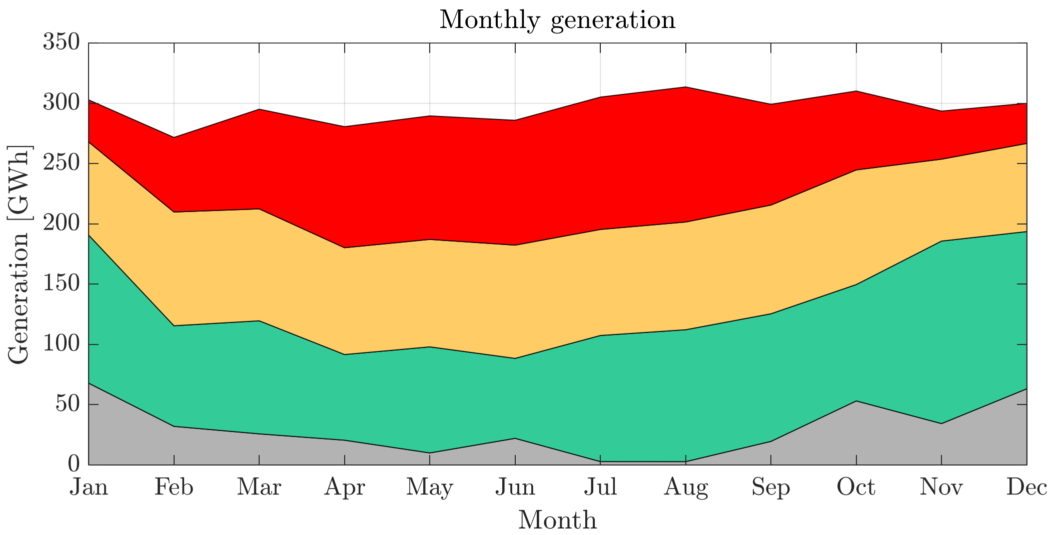


Figure 72. Example of operation of the solar thermal power plant

More specific results about daily and monthly generation are shown in Figure 73. The contribution of PV and solar thermal generation is higher in summer, while coal has to compensate for the lack of solar resources in winter. This can be clearly observed in Figure 74, where the hourly generation is depicted during ten days of January and August. During this period in August, the solar and wind resources are sufficient to supply all the demand. On the other hand, in January the coal generation is present during many days and it is also the main contributor during some days.

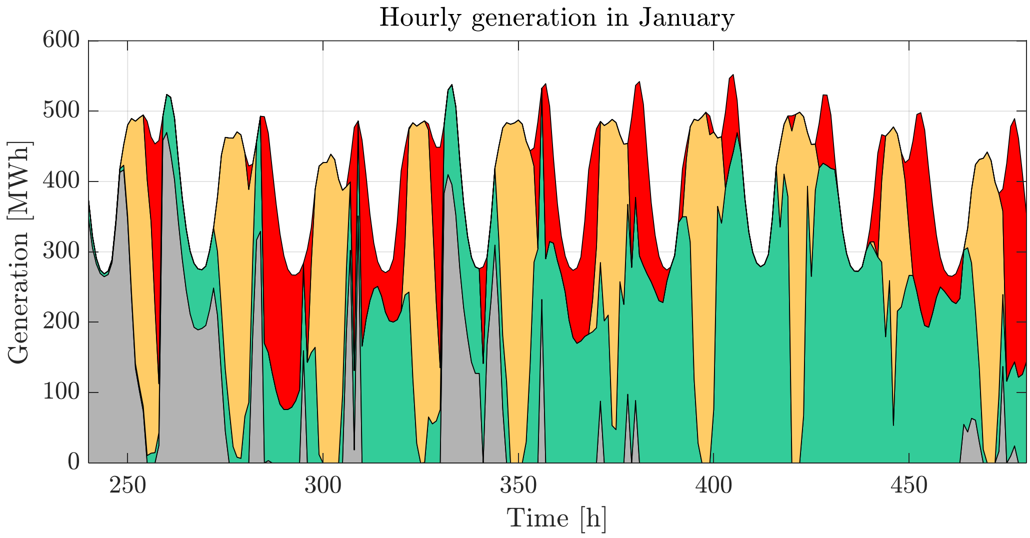


(a)

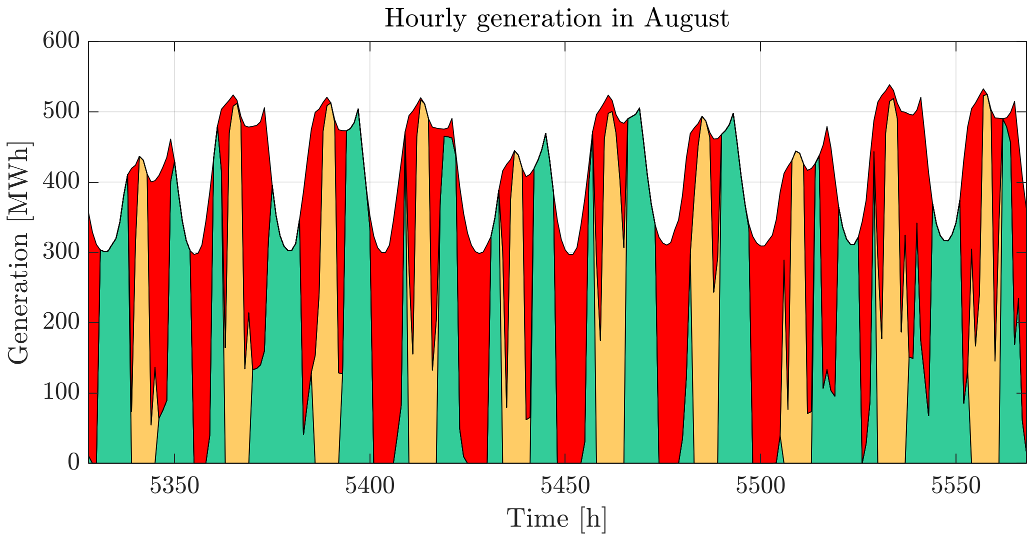


(b)

Figure 73. Generation mix for Case 2 in 2019: (a) daily; (b) monthly



(a)



(b)

Figure 74. Hourly generation for Case 2 during: (a) January; (b) August

The same grid configuration is considered in this second case, but including solar thermal (Figure 75). The conventional, wind and PV obtained capacities are very similar to the case without solar thermal, and thus the powers shown are the same as in the previous case. The additional solar thermal capacity is distributed equally in busses 4 and 6, in the same area where the PV is located.

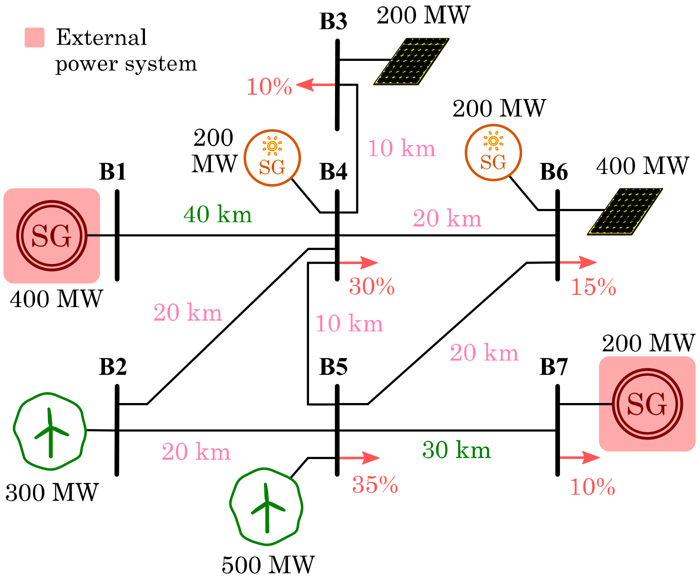


Figure 75. Scenario 2: Island without storage capability – Final proposed layout

3.2.2 Scenario 3: Type II – Synchronously interconnected (AC): northern Europe

The Scenario 3 corresponds to an AC interconnected system (Type II) located in northern Europe. This scenario has been specifically located in the Netherlands to extract the system demand and the solar and wind resources. The hourly consumption data of the Netherlands obtained from [63] has been scaled down to have a maximum instantaneous demand of 5 GW. Thus, the relevant demand numbers of this scenario are the following:

- Maximum demand: 18.02 GW (real data) → 5.00 GW (modified data)
- Average demand: 13.00 GW (real data) → 3.61 GW (modified data)
- Minimum demand: 8.55 GW (real data) → 2.37 GW (modified data)

The generation technologies included in this scenario are coal, wind, PV and pumping hydro. Three cases have been considered to analyze the effect of the water storage in the system:

- **Case 1**: no storage
- **Case 2**: pumping hydro generation with an installed capacity equal to the 10% of the maximum demand.
- **Case 3**: pumping hydro generation with an installed capacity equal to the 20% of the maximum demand.

For Cases 2 and 3, the pumping hydro generation is assumed to be already installed, so the capital cost is not considered.

Figure 76 shows the wind and PV capacity required based on the minimum renewable share. It is observed that the presence of the pumping hydro generation can help to reduce considerably the amount of renewable generation. For α = 90%, the wind capacity obtained for Case 1 is around 24 GW, while it is reduced to 19 GW for Case 2 and to 15 GW for Case 3. So, a reduction of almost 10 GW of wind power can be achieved only including 1 GW of pumping hydro generation. This results in a reduction of the generation costs of the system. Figure 77 shows the generation costs for the three cases. The costs have been normalized considering Case 3 as the base case. It can be observed that Case 3 provides a cost around 50% and 20% lower respect to Case 1 and Case 2 when α = 90%. For higher values of α, higher cost reductions are achieved, as the pumping hydro generation avoids the installation of new wind and PV generation. However, it must be noted that the capital cost of pumping hydro generation has not been considered. In that case, the cost reduction obtained would be lower.

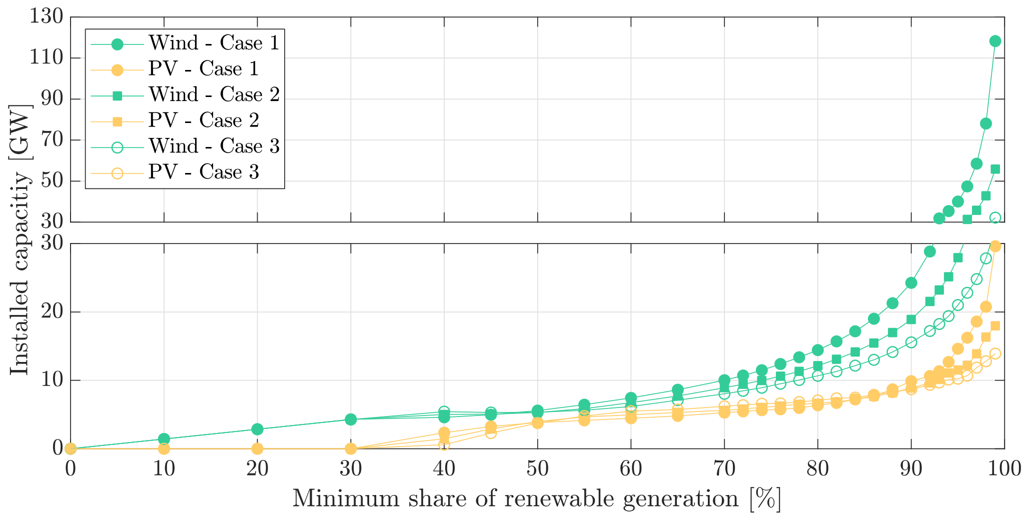


Figure 76. Installed capacity of wind and PV for the three cases and α = 0 to 99%

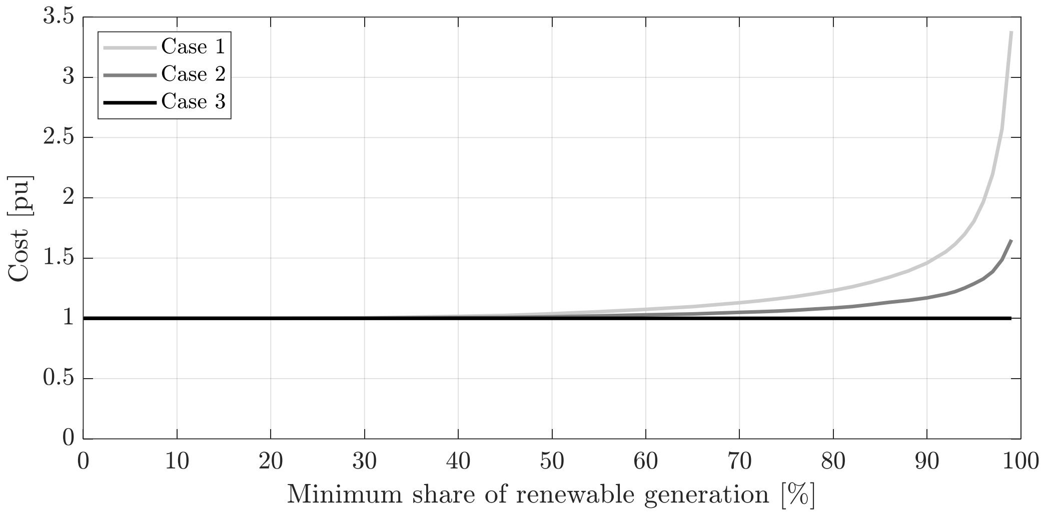
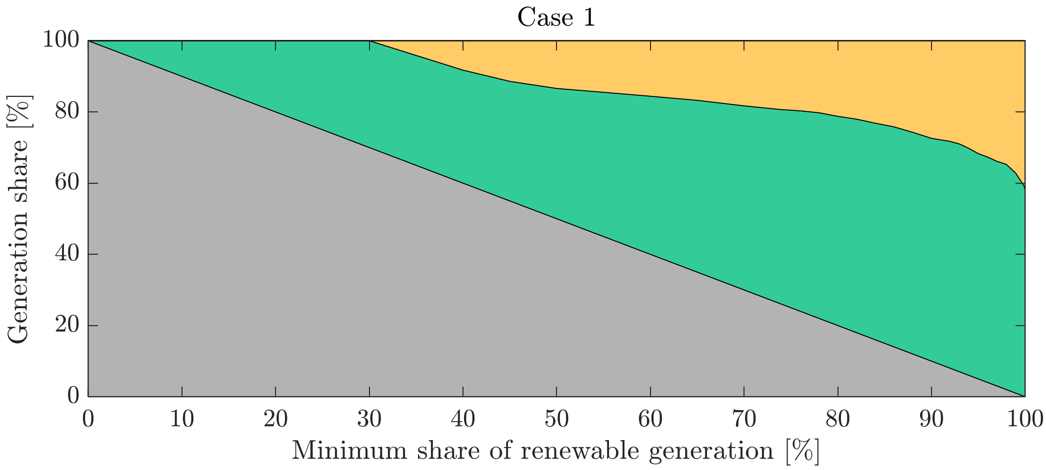


Figure 77. Total generation cost considering Case 3 as the base case

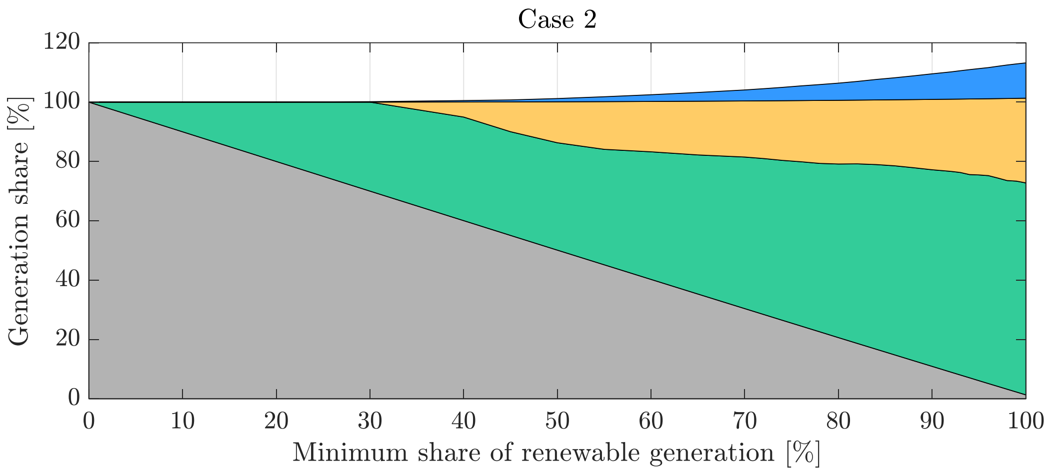
The generation share based on the minimum renewable generation is depicted in Figure 78 for the three cases. Coal, wind and PV generation share the demand according to the minimum renewable share restriction. The hydro generation is always above 100%, as the net energy contribution of the pumping hydro is null. The use of hydro generation rises when α is increased, allowing to store energy and save the installation of wind or PV. It can be observed that in Cases 2 and 3, the coal generation is different from zero when α is set to 100%. The restriction in (18) ensures that the wind and PV generation is equal to the system demand. When the pumping hydro is included, this demand is increased due to the pumping consumption. A reduced part of the pumping consumption is supplied by the coal generation.

A further analysis has been carried out when α = 74%. Figure 79 shows the installed capacity and annual generation for all the cases. The installation of the hydro pumping allows to supply nearly the same amount of renewable generation for the three reducing the installed capacity of wind and PV for Cases 2 and 3.

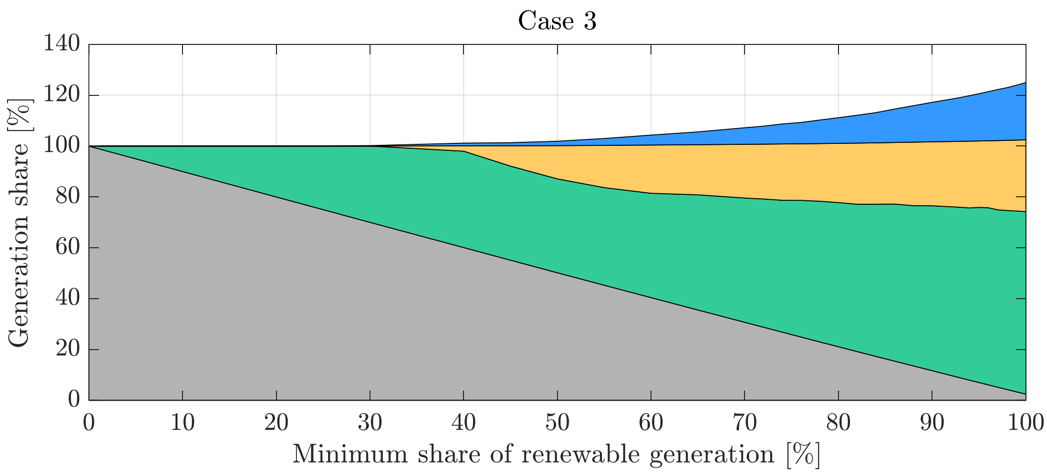
Specific daily, monthly and hourly results of Case 3 are shown in Figure 80. In this case, the PV generation varies along the year, as Scenario 3 is located in a higher latitude compared to Scenario 1. Figure 80.c shows how the pumping is used when there is a high renewable generation, helping to reduce the generation cost.



(a)

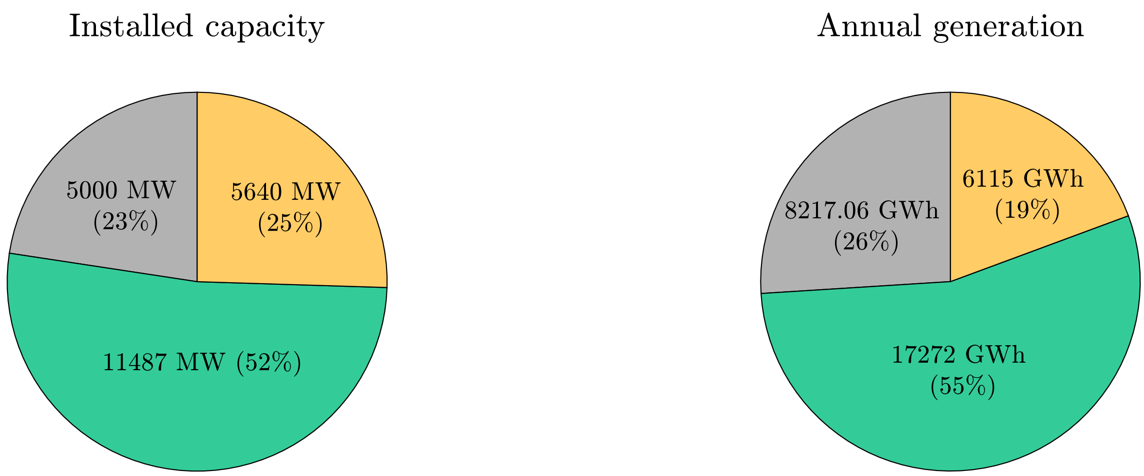


(b)

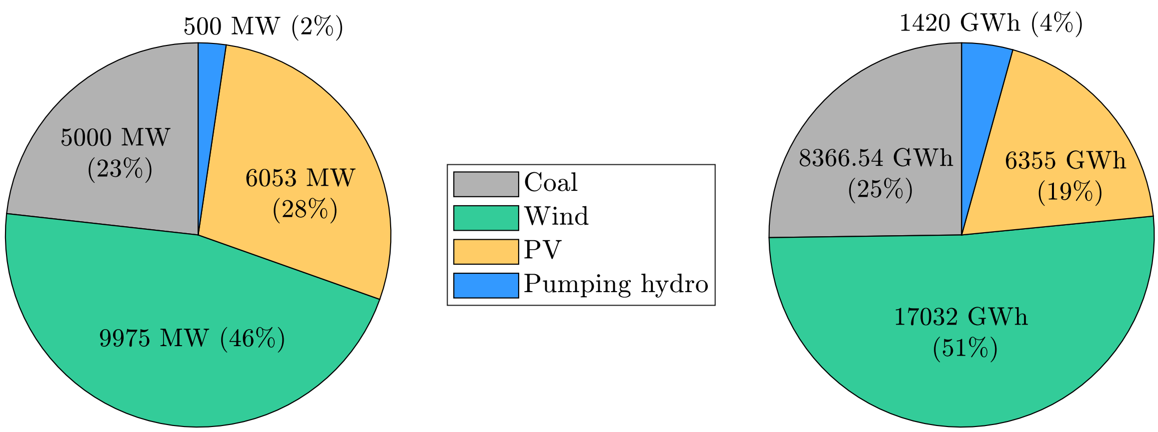


(c)

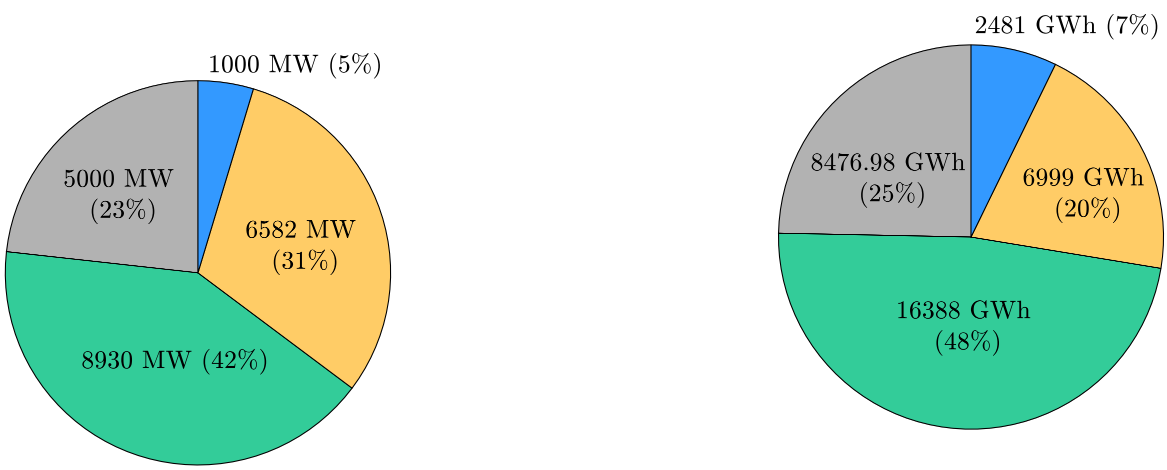
Figure 78. Generation share based on the minimum renewable required for: (a) Case 1; (b) Case 2; (c) Case 3



(a) Case 1



(b) Case 2



(c) Case 3

Figure 79. Installed capacity and annual generation mix for $\alpha = 74\%$

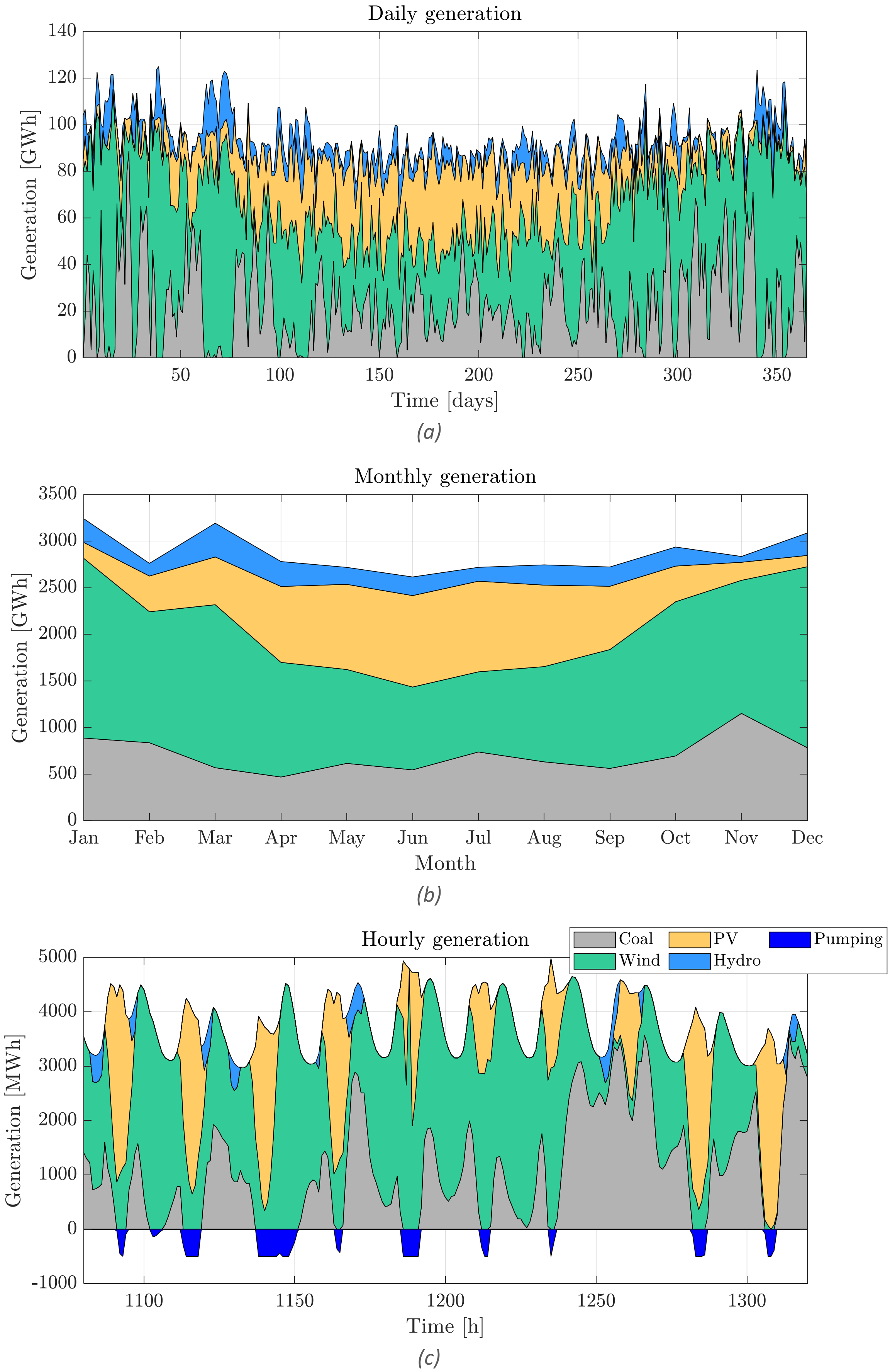


Figure 80. Daily, monthly and hourly generation for Case 3 and $\alpha = 74\%$

Based on the results obtained, and on the preliminary layout from Section 2.4, the final scenario is depicted in Figure 81. The scenario contains a total number of 8 transmission busses and 5 distribution busses. The large size of the different power plants does not represent a single power plant, but an aggregated equivalent of several ones. The voltage levels of the transmission lines could be, for instance, in the range of 220-400 kV, whereas in the distribution case it could be 20-30 kV. A relevant amount of offshore wind (both DC-interconnected and AC-interconnected) is considered, as this scenario is inspired in the north of Europe. Also, onshore wind, PV and hydro pumping is considered, as well as a portion of conventional generation. The loads are more present in the center of the grid, and the rest is distributed in the peripheric busses.

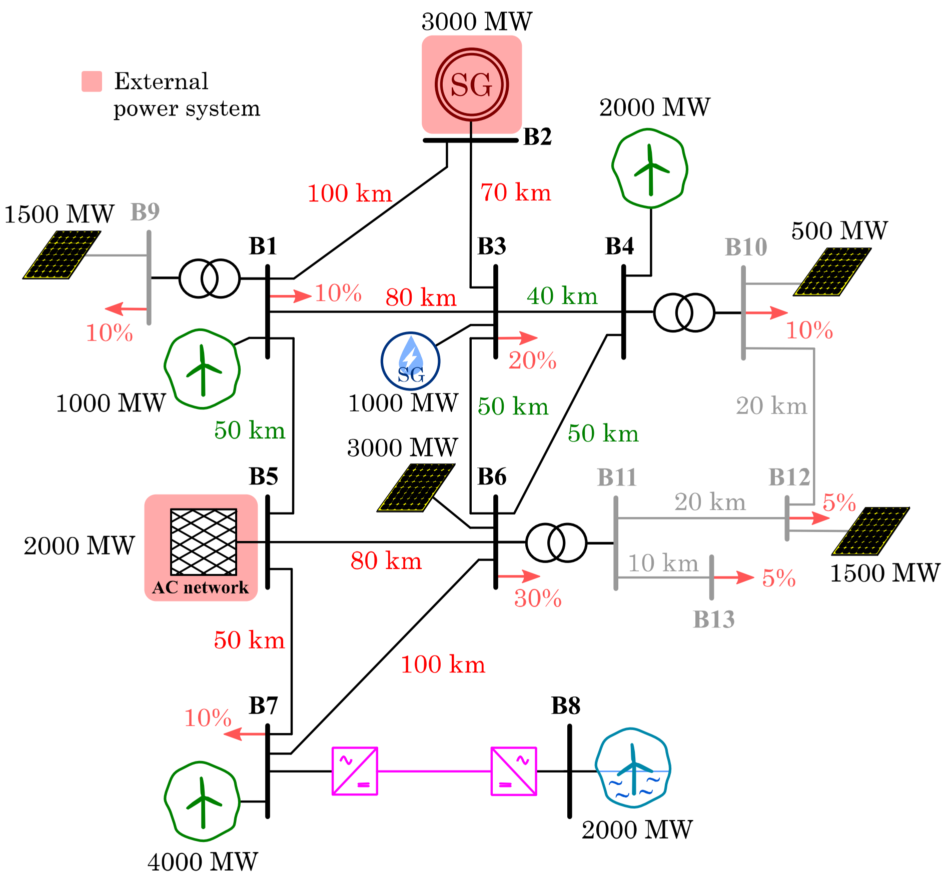


Figure 81. Scenario 3 – Final proposed layout

3.3 Additional scenario: Centre-West France

An additional scenario has been considered. In particular, the synchronously connected case based on the Centre-West grid of France has been added. The considered area is shown in Figure 82. More details about the buses included in this scenario are shown in Figure 83. Based on the grid included in this scenario, the final layout is shown in Figure 84, which includes 17 buses, 220-kV and 440-kV transmission lines, 3 nuclear power plants, 3 hydro power plants (which group smaller power plants connected nearby), one PV power plant and one wind power plant.

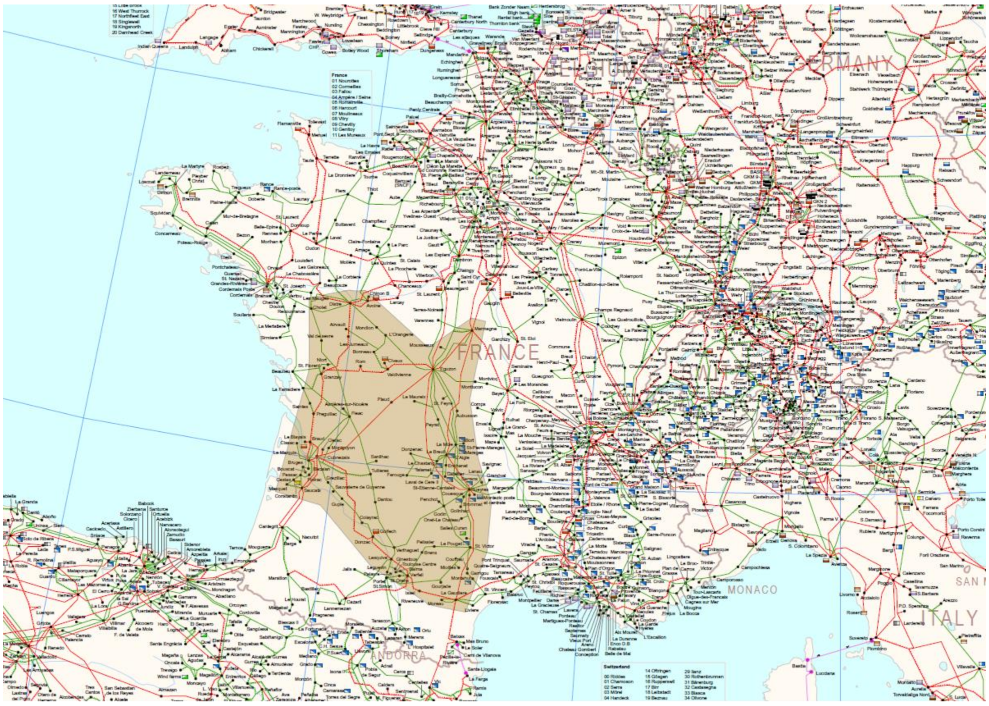
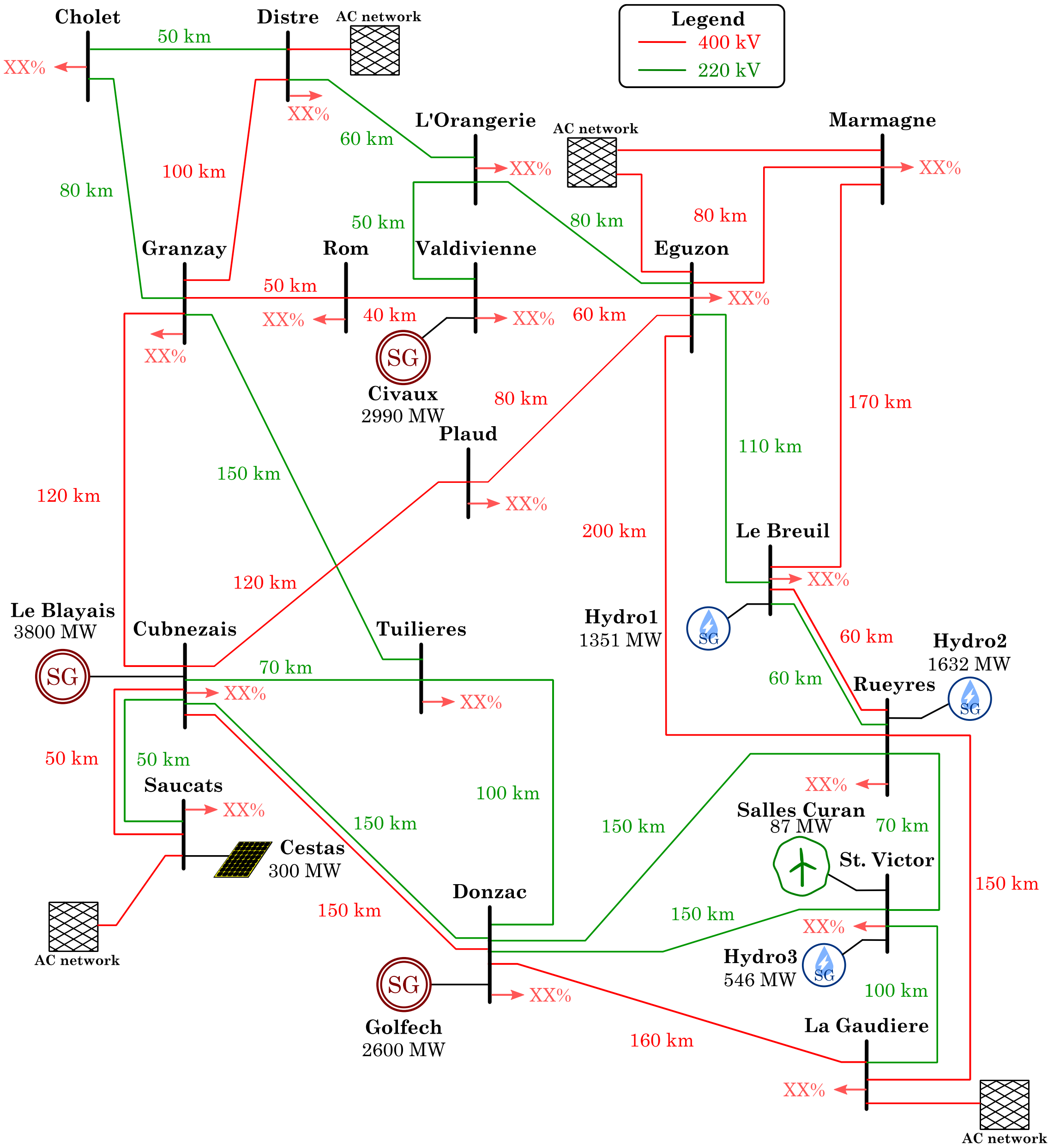


Figure 82. Area considered in the Centre-West France scenario

Figure 83. Buses included in the Centre-West France scenario



Hydro1: Bort (230 MW) + St-Pierre (120 MW) + Mareges (144 MW) + L'Aigle (349 MW) + Le Chastang (293 MW) + Laval de Cere II (108 MW) + St-Etienne-Cantales (107 MW)

Hydro2: Sarrans (183 MW) + Couesque (119 MW) + Brommat (420 MW) + Montezic (910 MW)

Hydro3: Le Pouget (446 MW) + Montahut (100 MW)

Figure 84. Centre-West France scenario - Layout

4 Conclusions

The deliverable has analyzed different possible scenarios that can be used for the analysis of realistic Virtual Power Plants in Europe. The design of the scenarios has been done considering specific weather conditions and renewable resources of specific regions, and an optimization-based methodology has been developed to quantify the amount of renewable generation capacity needed. Different renewable energy technologies have been considered, in order to meet specific requirements of grid integration of renewables at different horizons of time, up to 100 % in the most futuristic case.

It has been shown that some technologies can provide the renewable backbone (solar PV and wind) but at the same time they lack the flexibility needed to achieve a very high penetration. Other technologies become important to cover the last range of integration (for instance, solar thermal and pumped hydro), as they are expensive for low penetration but they provide a high flexibility, which is crucial for high penetration. Otherwise, if these technologies are excluded, the required installed capacity if, for instance, only wind and PV are considered, might rise substantially for high renewable penetration level constraints, as discussed in the previous section.

The presented scenarios do not pretend to give detailed recommendations on energy system planning. They have been presented as examples of the proposed methodology. These examples can be considered realistic in the sense that they are inspired in real data and real locations to some extent, but they are neither detailed nor final studies. As the current power system still contains a large amount of conventional thermal power plants, the current network configuration and the presence of renewable power plants might be subject to important changes over the next years and decades. The proposed scenarios can be seen as a starting point for further studies within the Posytyf project (e.g., work package 5) and other related studies. Throughout the project, these scenarios may evolve considering the feedback and the needs of the corresponding work packages.

References

[1] European Commission, "EC Communication: United in delivering the Energy Union and Climate Action - Setting the foundations for a successful clean energy transition. COM/2019/285 final," Brussels, Belgium, 18 June 2019.

[2] European Council, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources.," Brussels, Belgium, 5 June 2009.

[3] European Council, "Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast).," Brussels, Belgium, 11 December 2018.

[4] European Commission, "Clean energy for all Europeans package," European Commission Website, Brussels, Belgium, 2019.

[5] European Council, "Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action. PE/55/2018/REV/1," Brussels, Belgium, 2018.

[6] European Commission, "National Energy and Climate Plans," European Commission Website, Brussels, Belgium, 2020.

[7] European Commission, "EC Communication: An EU-wide assessment of National Energy and Climate Plans Driving forward the green transition and promoting economic recovery through integrated energy and climate planning. COM/2020/564 final," Brussels, Belgium, 17 September 2020.

[8] Ministerio para la Transición Ecológica y el Reto Demográfica, "Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030," January 2020.

[9] Protermosolar, "Asociación Española para la Promoción de la Industria Termosolar".

[10] European Council, "Presidency Conclusions of the Brussels European Council 29/30 October," Brussels, Belgium, 1 December 2009.

[11] IRENA, "Global Renewables Outlook: Energy transformation 2050," Abu Dhabi: International Renewable Energy Agency (IRENA), April 2020.

[12] European Comission, "Energy roadmap 2050," Luxembourg: Publications Office of the European Union, 2012.

[13] SolarPower Europe and LUT University, "100% Renewable Europe: How To Make Europe's Energy System Climate-Neutral Before 2050," 2020.

[14] G. Resch, F. Schöniger, C. Kleinschmitt, K. Franke, F. Sensfuß, R. Thonig and J. Lilliestam, "Market uptake of concentrating solar power in Europe: model-based analysis of drivers and policy trade-offs. Deliverable 8.2 of the Horizon 2020 project MUSTEC [GA No. 764626]," Vienna, Austria: TU Wien, 2020.

[15] S. Awerbuch and A. M. Preston, The virtual utility : accounting, technology & competitive aspects of the emerging industry, Boston: Kluwer Academic Publisher, 1997.

[16] G. Zhang, C. Jiang and X. Wang, "Comprehensive review on structure and operation of virtual power plant in electrical system," *IET Generation, Transmission & Distribution,* vol. 13, no. 2, pp. 145-156, 2019.

[17] International Electrotechnical Commission, "IEV ref 617-04-22," 15 December 2017. [Online]. Available: www.electropedia.org/iev/iev.nsf/display?openform&ievref=617-04-22.

[18] D. Infield and L. Freris, Renewable Energy in Power Systems, 2nd Edition, 2020, January.

[19] D. Van Hertem, O. Gomis-Bellmunt and J. Liang, HVDC Grids for Offshore and Supergrid of the Future, Hoboken, New Jersey, USA: Wiley & Sons, Inc., 2016.

[20] H. Abu-Rub, M. Malinowski and K. Al-Haddad, Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications, 2014, July.

[21] Environmental and Energy Study Institute (EESI), "Fact Sheet: Energy Storage (2019)," 2019, February.

[22] European Energy Research Alliance (EERA), "EERA Joint Program SP4 - Mechanical Storage, Fact Sheet 1 - Nov 2016, Pumped Hydro Energy Storage," 2016, November.

[23] International Renewable Energy Agency (IRENA), "Geothermal energy," 2020. [Online]. Available: https://www.irena.org/geothermal.

[24] National Renewable Energy Laboratory (NREL), "Geothermal Electricity Production Basics," 2020. [Online].

[25] ENDESA, "Central térmica convencional," [Online]. Available: https://www.fundacionendesa.org/es/centrales-electricas-convencionales/a201908-central-termica-convencional.

[26] ENDESA, "Central térmica de ciclo combinado," [Online]. Available: https://www.fundacionendesa.org/es/centrales-electricas-convencionales/a201908-central-termica-convencional-ciclo-combinado.

[27] T. T.D. Tran and A. D. Smith, "Evaluation of renewable energy technologies and their potential for technical integration and cost-effective use within the U.S.

energy sector.," *Renewable and Sustainable Energy Reviews,* pp. 1372-1388, 2017.

[28] P. Denholm and T. Mai, "Timescales of Energy Storage Needed to Reduce Renewable Energy Curtailment: Report Summary," 2017, October.

[29] Energy Information Administration (EIA), "Levelized Cost and Levelized Avoided Cost of New Resources in the Annual Energy Outlook 2020," 2020, February.

[30] W. Kenton and D. Kindness, "Capital Expenditure (CapEx)," [Online]. Available: https://www.investopedia.com/terms/c/capitalexpenditure.asp.

[31] TheFreeDictionary, "Financial Glossary: Opex," 2011. [Online]. Available: https://financial-dictionary.thefreedictionary.com/Opex.

[32] E. Bullich-Massagué, R. Ferrer-San-José, M. Aragüés-Peñalba, L. Serrano-Salamanca, C. Pacheco-Navas and O. Gomis-Bellmunt, "Power plant control in large-scale photovoltaic plants: Design, implementation and validation in a 9.4 MW photovoltaic plant," *IET renewable power generation,* pp. 50-62, 2016.

[33] M. A. Gonzalez-Salazar, T. Kirsten and L. Prchlik, "Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables," *Renewable and Sustainable Energy Reviews,* vol. 82, no. 1, pp. 1497-1513, 2018.

[34] Office of Energy Efficiency & Renewable Energy, "Concentrating Solar-Thermal Power," 2020.

[35] International Renewable Energy Agency (IRENA), "Power System Flexibility for the Energy Transition. Part 1: Overview for Policy Makers," 2018, November.

[36] Energy Information Administration (EIA), "Capital Cost an Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies," 2020, February.

[37] The Intergovernmental Panel on Climate Change (IPCC), "Energy Systems. Figure 7.6 Comparative lifecycle greenhouse gas emissions from electricity supplied by commercially available technologies (fossil fuels, renewable, and nuclear power) and projected emissions of future commercial plants of currently pre-co," 2014.

[38] International Institute for Applied Systems Analysis (IIASA), "Global Energy Assessment Toward a Sustainable Future," 2012.

[39] Lazard, "Lazard's Levelized Cost of Energy Analysis - Version 14.0," 2020. [Online]. Available: https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf.

[40] International Renewable Energy Agency (IRENA), "Global Trends. Global weighted average total installed costs, capacity factors and LCOE 2010-2019,"

2020. [Online]. Available: https://www.irena.org/Statistics/View-Data-by-Topic/Costs/Global-Trends.

[41] Energy Information Administration (EIA), "Coal explained: coal prices and outlook," 2020. [Online]. Available: https://www.eia.gov/energyexplained/coal/prices-and-outlook.php.

[42] Energy Information Administration (EIA), "Natural Gas Prices," 2020, October. [Online]. Available: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm.

[43] J. A. Rico, "Costes y Rentabilidad de las Centrales Nucleares Españolas. Colegio de Ingenieros Industriales de Madrid," 26 Junio 2014. [Online]. Available: https://portal.coiim.es/uploads/files/f89af51b417d027ff2512fbf1b53ddc92e8afed5.pdf. [Accessed 3 Diciembre 2020].

[44] M. Sengupta, A. Habte, C. Gueymard, S. Wilbert and D. Renné, "Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Second Edition," 2017.

[45] A. Amillo, T. Huld and R. Müller, "A New Database of Global and Direct Solar Radiation Using the Eastern Meteosat Satellite, Models and Validation," *Remote Sensing,* vol. 6(9), pp. 8165-8189, 2014.

[46] T. Huld, R. Müller and A. Gambardella, "A new solar radiation database for estimating PV performance in Europe and Africa," *Solar Energy,* vol. 86, no. 6, pp. 1803-1815, 2012.

[47] A. Sanchez-Lorenzo, M. Wild and J. Trentmann, "Validation and stability assessment of the monthly mean CM SAF surface solar radiation dataset over Europe against a homogenized surface dataset (1983–2005)," *Remote Sensing of Environment,* vol. 134, pp. 355-366, 2013.

[48] M. Schroedter-Homscheidt et al, "User's Guide to the CAMS Radiation Service (CRS) Status December 2019. ECMWF Copernicus Report," 2019.

[49] MEASNET, "Evaluation of site-specific wind conditions. MEASNET procedure. Version 2," 2016.

[50] "WAsP Homepage," [Online]. Available: https://www.wasp.dk/.

[51] The European Union, "The European Commission´s Knowledge Center for Bioeconomy. JRC109354," 2019.

[52] International Hydropower Association, "Hydropower Status Report," 2020.

[53] Red Eléctrica de España, "El sistema eléctrico canario," 2016. [Online]. Available:

https://www.ree.es/sites/default/files/downloadable/diptico_canarias_2016_esp.pdf.

[54] Electricidade dos Açores, "Caracterização das redes de transporte e distribuição de energia eléctrica," 2019. [Online]. Available: https://www.eda.pt/EDA/DocsDistribuicao/CARE%202019.pdf.

[55] ENTSO-E, "Interconnected network of Continental Europe," 2019. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/Publications/maps/2019/Map_ENTSO-E-4.000.000.pdf.

[56] "renewables.ninja," [Online]. Available: https://www.renewables.ninja/. [Accessed January 2021].

[57] SolarPACES, "CSP Projects around the world," IEA Technology Collaboration Programme, [Online]. Available: http://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/. [Accessed February 2021].

[58] M. Biencinto, L. González, L. Valenzuela and E. Zarza, "A new concept of solar thermal power plants with large-aperture parabolic trough collectors and sCO2 as working fluid," *Energy Conversion and Management,* no. 199, September 2019.

[59] L. Valenzuela, R. López-Martín and E. Zarza, "Optical and thermal performance of large-size parabolic-trough solar collectors from outdoor experiments: A test method and a case study," *Energy,* no. 70, pp. 456-464, 2014.

[60] NOAA, "Global Monitoring Laboratory. Solar Calculation Details," [Online]. Available: https://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html. [Accessed January 2021].

[61] REE, "ESIOS. Sistema de información del operador del sistema," [Online]. Available: https://www.esios.ree.es/en. [Accessed January 2021].

[62] Spanish government, "Plan nacional integrado de energía y clima 2021-2030," 2020.

[63] Open Power System Data, "Data Platform. Time series," [Online]. Available: https://data.open-power-system-data.org/time_series/. [Accessed January 2021].

[64] NEWA ERA-Net Plus Project, "Link to Global Wind Atlas and National Wind Atlases. Deliverable D4.7," 2018.

[65] Bioenergy Europe, "Biomass supply report 2019," 2019. [Online]. Available: https://bioenergyeurope.org/article/178-biomass-supply-report.html.

[66] IRENA, "Renewable Capacity Statistics 2020," Abu Dhabi: International Renewable Energy Agency (IRENA), March 2020.

[67] T. Patsialis, I. Kougias, N. Kazakis, N. Theodossiou and P. Droege, "Supporting Renewables' Penetration in Remote Areas through the Transformation of Non-Powered Dams," *Energies,* vol. 9, no. 1054, 2016.

[68] U. Schwarz et al, "Hydropower pressure on European rivers. The story in numbers," 2019.