FlexPlan

Advanced methodology and tools taking advantage of storage and FLEXibility in transmission and distribution grid PLANning

Pan-European scenario data

D4.1

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About FlexPlan

The FlexPlan project aims at establishing a new grid planning methodology considering the opportunity to introduce new storage and flexibility resources in electricity transmission and distribution grids as an alternative to building new grid elements. This is in line with the goals and principles of the new EC package *Clean Energy for all Europeans,* which emphasizes the potential usage of flexibility sources in the phases of grid planning and operation as alternative to grid expansion. In sight of this, FlexPlan creates a new innovative grid planning tool whose ambition is to go beyond the state of the art of planning methodologies, by including the following innovative features: integrated T&D planning, full inclusion of environmental analysis, probabilistic contingency methodologies replacing the N-1 criterion as well as optimal planning decision over several decades. However, FlexPlan is not limited to building a new tool but it also uses it to analyse six regional cases covering nearly the whole European continent, aimed at demonstrating the application of the tool on real scenarios as well as at casting a view on grid planning in Europe till 2050. In this way, the FlexPlan project tries to answer the question of which role flexibility could play and how its usage can contribute to reduce planning investments yet maintaining (at least) the current system security levels. The project ends up formulating guidelines for regulators and for the planning offices of TSOs and DSOs. The consortium includes three European TSOs, one of the most important European DSO group, several R&D companies and universities from 8 European Countries (among which the Italian RSE acting as project coordinator) and N-SIDE, the developer of the European market coupling platform EUPHEMIA.

Partners

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List of Abbreviations and Acronyms

Abbreviation/Acronym	Meaning
B	Susceptance
CGMES	Common Grid Model Exchange Specification
CHP	Combined Heat and Power
DE	Distributed Energy
DG	Distributed Generation
DSO	Distribution System Operator
DSR	Demand Side Response
EHV	Extra High Voltage
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSOs	European Network of Transmission System Operators for Electricity and Gas
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
GA	Global Ambition
GCA	Global Climate Action
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HPP	Hydro Power Plant
HV	High Voltage
HVDC	High Voltage Direct Current Medium Voltage
LV	Low Voltage
MAF	Mid-term Adequacy Forecast
MILES	Model of International Energy Systems
MV	Medium Voltage
NDA	Non-Disclosure Agreement
NECP	National Energy and Climate Plans
NT	National Trends
NTC	Network Transfer Capacity
P2G	Power-to-Gas
PPM	Power Plant Matching
R	Resistance
RC	Regional Case
RES	Renewable Energy Sources
ST	Sustainable Transition
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
X	Reactance

Executive Summary

This deliverable documents the outputs of Tasks 4.1 and 4.2 of FlexPlan, whose activities are related to data collection, harmonization and processing for usage at two different levels: pan-European simulations to be performed in the following tasks of WP4 and the execution of the six designed regional cases in WP5.

FlexPlan aims to develop an innovative grid planning tool, which results, in this particular case, in ambitious and complex data collection and data processing activities. These involve the collection of heterogeneous data from multiple data sources, followed by a comprehensive data harmonization/data processing work, paving the way for the simulation of Pan-European power system in a first step and the execution of six comprehensive and detailed regional cases in a second step. Data collected is included into three main categories, necessary to execute the following FlexPlan activities. These categories include:

- Pan-European Scenarios: macroscopic scenarios, detailing the energy landscape at national level and including different time horizons. These should include figures such as installed capacity, energy generation and consumption time-series and other complementary parameters necessary for power system simulation in the current context (e.g. NTC and commodity prices)
- Grid models: comprehensive grid models to be used at regional case level, including transmission and distribution grids. These must include detailed and complete information regarding not only the grid topology but also geographic location of grid nodes and general information on generation units.
- Other complementary data: additional datasets needed to ensure a full demonstration of the FlexPlan tool capabilities, allowing to study the impact on landscape, air quality and carbon footprint of selected grid expansion candidates.

This document contains a full description of the collected data, identified used data sources and describes implemented methodologies for data harmonization and processing activities, establishing also the basis for the next activities to be performed in FlexPlan, using these data. It is mostly focused in the description of the created pan-European Scenarios, describing also other datasets identified and used in the scope of FlexPlan. In summary, it documents the Pan-EU scenarios created in FlexPlan, together with the main findings in the creation of these scenarios and performed analysis of grid models and additional data needs.

1 Introduction

FlexPlan aims to deliver an innovative grid planning tool, validated using six regional cases covering almost all the European power system area. The execution of these regional cases needs to be led by a complex and ambitious process of data collection, validation and processing, as they will be thoroughly studied using three different target years: 2030, 2040 and 2050. The collection of data for the creation of scenarios that can be simulated is the main goal of FlexPlan Tasks 4.1 and 4.2, and this deliverable is the documented output of these activities. Figure 1-1 depicts the overall chain of activities to be performed in FlexPlan, highlighting the collection of data for scenario built.

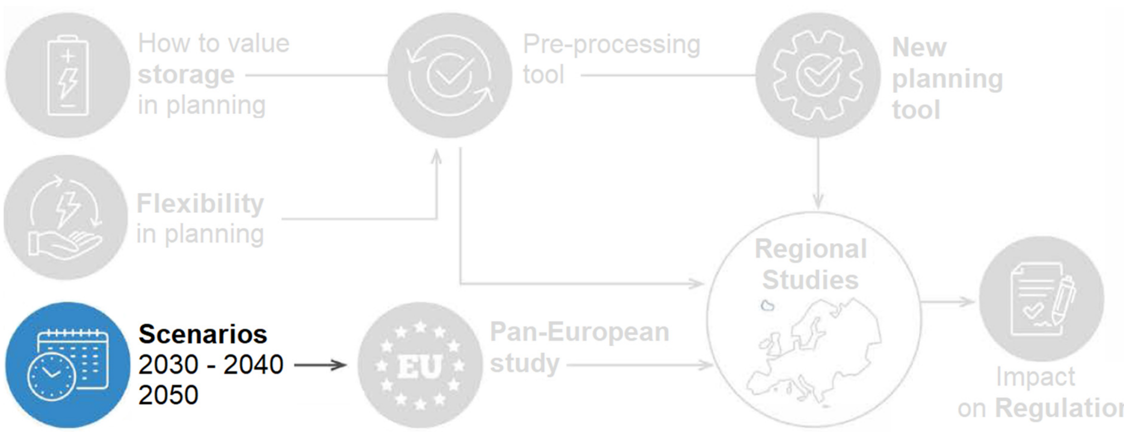


Figure 1-1 - FlexPlan chain of activities.

The regional case studies of FlexPlan cover almost all central and Western Europe and also the Nordic countries, as indicated in Figure 1-2. As FlexPlan has several ambitious goals, the execution of each regional case resorts to the existence of a multitude of datasets, which will result in comprehensive grid models. These grid models, corresponding to each regional case, also need to be coherent at pan-European level, thus respecting different border conditions and including existing/planned interconnections, core to the existing and future European power system.

FlexPlan regional cases are then built using many heterogeneous data, which needs to be effectively analysed and converted into a single dataset to be used as input for the planning tool. The data needs to cover the following three main aspects:

- Pan-EU Scenarios;
- Grid Models – including transmission and distribution grids;
- Other complementary datasets.

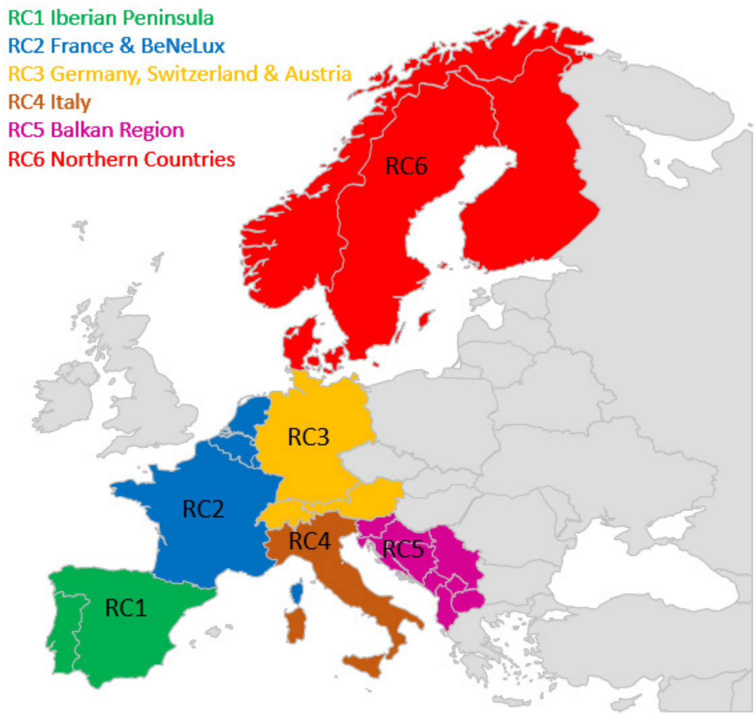


Figure 1-2 - FlexPlan Regional Cases.

The presentation of the created pan-EU scenarios is the main topic of this document. However, since the performed activities in the collection and processing of data related to the other two covered aspects involved a significant effort, these should be presented as well.

To test the implemented planning tool using the six presented regional cases (Figure 1-2), different scenarios should be considered. These scenarios correspond to different grid operational conditions (different power flows) and using different target years. For this purpose, FlexPlan applies a multi-step modelling approach.

In a first phase, pan-European scenarios are set up for the target years 2030, 2040 and 2050 in order to perform a pan-European study. For each year, three divergent scenario variants are considered, resulting in a set of nine scenarios in total. A European market coupling simulation is carried out for each of the nine scenarios in order to derive trans-regional border conditions. These divergent scenario variants are derived from major political drivers in coherence with European Network of Transmission System Operators for Electricity (ENTSO-E) Ten-Year Network Development Plan (TYNDP)[1].

In a second phase, the regional case studies will be carried out. These case studies include a by far more detailed representation of the grid, but must necessarily have a smaller geographic scope, e.g.

[1] ENTSO-E TYNDP2020 and TYNDP2018

mainly only one to three countries. This activity is the scope of Work Package 5 of FlexPlan and therefore is not further detailed in this document.

With regard to the pan-European study indicated as the first phase, the electricity market and transmission grid simulation framework *MILES* (Model of International Energy Systems) is applied. The FlexPlan multi-step modelling approach is depicted in Figure 1-3. A more detailed description is given in Appendix A.

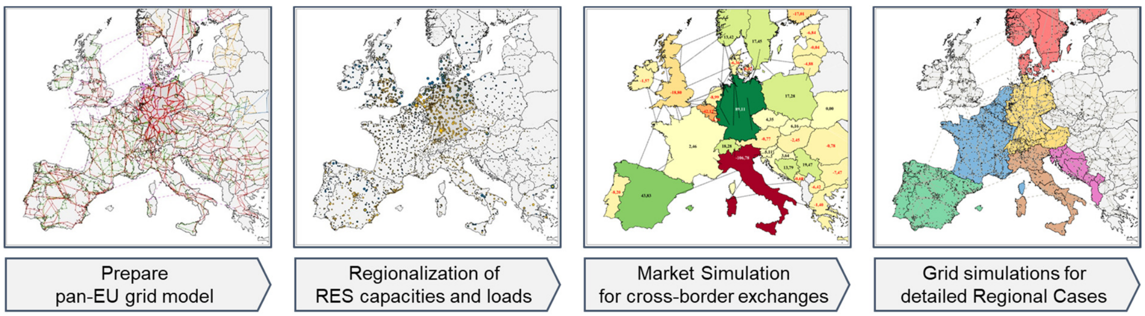


Figure 1-3 - Multi step modelling approach.

The regionalization module of *MILES* calculates installed capacities at zonal level as well as time series for feed in of Renewable Energy Sources (RES) for 34 countries in Europe, starting from National level installed capacities defined in the Pan-EU scenarios. To distribute installed capacities of RES, *MILES* applies a top down approach. National territory of each country is divided in sub-regions. Subsequently various statistical figures for each region are analysed carefully to generate regionalization factors. The considered statistical parameters include socio-structural data, land use, location of existing plants and weather related data. In a second step *MILES* calculates feed-in time series for each region based on historical weather data and the assigned installed capacities. The weather data processed in *MILES* are taken from the regional model *COSMO-EU* of Germany's National Meteorological Service. Table 1-1 includes the considered number of sub-regions for each one of the countries to be considered in the FlexPlan regional cases.

A historical load profile is broken down by means of regionalization factors and scaled to the targeted annual consumption, to generate spatially disaggregated time-series of the electrical load in each sub-region. For the electrical load, a distinction must be made between the load of the household, services and industry sectors. The number of households or the population of every region is used as main parameters for the household sector. The regional distribution of the electrical load of the business sector is described by several parameters without considering any weighting parameters. The Gross Domestic Product (GDP) and population density are major indicators for the electrical energy demand. Other main parameters are the area of commercial buildings and related open space and the working population of each sub-region.

The market simulation module of *MILES* runs an integrated unit commitment and dispatch model determining power plant and storage schedules as well as cross-border power exchanges between European countries. Therefore, the fundamental market model of *MILES* solves a long-term Security

Constrained Unit Commitment optimization problem. Thereby, the objective aims at minimizing the total variable power generation costs in Europe. The optimal solution is constrained by different technical and economic requirements. On a system-wide level, the electrical load and the control reserve requirements have to be covered in each zone in every time step, taking into account generation unit's operational limits, such as minimum up- and down times, ramping limits and storage capacities of hydro units. The problem is formulated as a Mixed-Integer Linear Program with a rolling horizon of 10 days, which means the yearly simulation is divided in consecutive intervals of 240 hours each that are solved sequentially with a significant overlap (72 h) in the simulation horizon. The rolling window approach is depicted in Figure 1-4 [1]–[3].

Regional Case	Countries	Number of Sub-regions
1	Spain	599
	Portugal	404
2	France	766
	Netherlands	37
	Luxembourg	11
	Belgium	46
3	Denmark	162
	Norway	168
	Sweden	175
	Finland	70
4	Italy	728
5	Serbia	79
	Macedonia	103
	Albania	165
	Montenegro	67
	Bosnien Herzogovina	240
	Croatia	233
	Slovenia	174
6	Germany	732
	Austria	70
	Switzerland	126

Table 1-1 - Sub-regions per FlexPlan regional case.

The new innovative planning tool then uses the pan-EU results as hourly generation-load-configurations for running the considered regional cases throughout Europe. The six regional cases are built using scenario data coming from the aforementioned pan-European scenarios, together with additional data sources integrating such data in order to create the comprehensive datasets, which are then used to run the proposed planning tool. Grid topological data are mainly collected from ENTSO-E TYNDP 2018 Grid Model together with additional data sources used in order to add geographic information and real characteristics of existing/planned power plants for each regional case.

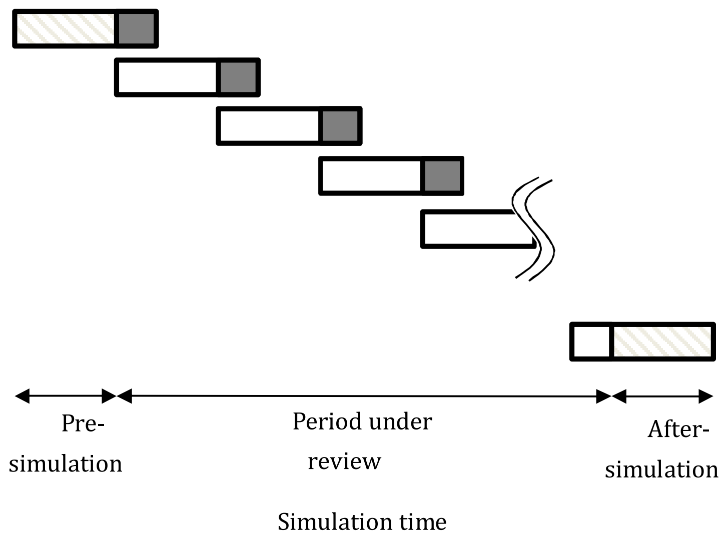


Figure 1-4 - Rolling optimization period.

This document is organized as follows: Section 2 contains a full description of the methodology used to create the pan-European scenarios and summarized input data for these scenarios and the three considered target years. Section 3 contains a description of collected data related to the grid modelling, both for transmission and distribution grids. Section 4 contains a description of all additional data needs identified and corresponding data sources, to ensure a full scope deployment of the FlexPlan tool. Finally, section 5 draws some conclusions regarding the document and its contents.

2 Pan-EU Scenarios

FlexPlan aims to validate the developed innovative grid-planning tool using six regional cases and three target years (2030-2040-2050). Additionally, and to further demonstrate the tool capabilities and allow for achieving more sound results, multiple scenarios for load and generation should be considered. These represent different visions for the European power system in these three target years. The main activity performed in the tasks reported here is indeed the creation of these scenarios, which should be based on well-know and accepted open source data sets. For this reason, the team chose to use TYNDP from ENTSO-E as the main data source and to create three scenarios per target year, which should be as much as possible a direct translation of ENTSO-E TYNDP scenarios. This section contains the description of the different scenarios considered and the methodology for the creation of the FlexPlan Pan-EU scenarios.

2.1 Scenarios considered

In the scope of work of the FlexPlan project, three target years are considered, as they describe the development of the power system up to 2050, which is the time horizon for reducing EU-28 emissions to net-zero in line with the United Nations Climate Change Conference 2015 (COP 21) targets. The scenarios for these target years need to take into account different restrictions in using primary energy resources such as coal, oil, gas and nuclear fuel. Also economic and socio-political aspects need to be taken into account as well as environmental aspects. FlexPlan approach to create these scenarios is to use a well-known and already validated data source, thus minimizing required efforts to validate the data collected or avoiding the need to use multiple sources, which would provide heterogeneous data.

The main source for the scenarios considered in FlexPlan project is the TYNDP, developed by ENTSO-E. The latest version of this report is ENTSOs' TYNDP 2020 [4] , which describes possible European energy futures up to 2050. TYNDP 2020 is not yet completed, and the full report is foreseen only for March 2021. However, ENTSOs already released the methodological reports, where the description of the used scenarios is present, together with scenarios data, already available [5] . It is important to mention, that the scenarios in TYNDP 2020 are not forecasts, they describe possible future conditions for the electricity and gas infrastructure, used by ENTSOs. The scenarios are ambitious as they deliver a low carbon energy system for Europe by 2050. The ENTSOs have developed credible scenarios, which reflect the characteristics of different countries, so that a pan-European low carbon future is achieved.

Scenarios from TYNDP 2020 are a prerequisite for any study analysing the future of the European energy system. All scenarios head towards a decarbonised future and have been designed to reduce greenhouse gas (GHG) emissions in line with EU targets for 2030 or COP21 Paris Agreement objective of keeping temperature rise below 1.5° C.

The joint scenario building process has three storylines for TYNDP2020. **National Trends** is the central policy scenario of TYNDP 2020 report, designed to reflect the most recent EU member state National Energy and Climate Plans (NECP), submitted to the European Commission in line with the requirement to meet current European 2030 energy strategy targets. **National Trends** represents a policy scenario used in the infrastructure assessment phase of the ENTSOs' relevant TYNDP 2020, with a more in-depth analysis than other scenarios.

In addition, ENTSO-E and ENTSO-G have created two scenarios in line with the COP 21 targets (**Distributed Energy** and **Global Ambition**) with the objective to understand the impact on infrastructure needs against different pathways reducing EU-28 emissions to net-zero by 2050.

Also it is important to note, that since the TYNDP 2020 Report is under development, it is necessary to use TYNDP 2018 as the second source of information. The TYNDP 2018 scenarios cover 2020 to 2040. Though 2020 and 2025 scenarios are labelled as best-estimate scenarios due to a lower level of uncertainty, the 2030 and 2040 scenarios have been designed with European 2050 targets as an objective, recognising the work done in the e-Highway 2050 project. The three main scenarios are considered in TYNDP 2018: Sustainable Transition (ST), where targets reached through national regulation, emission trading schemes and subsidies, maximising the use of existing infrastructure, Distributed Generation (DG), which embraces a de-centralised approach to the energy transition and Global Climate Action (GCA) with full-speed global decarbonisation, large-scale renewables development and economic development in centralised generation. Thus, in the absence of some information in the TYNDP 2020, it can be argued that the National Trends (NT), Distributed Energy (DE) and Global Ambition (GA) scenarios from TYNDP 2020 correspond to Sustainable Transition (ST), Distributed Generation (DG) and Global Climate Action (GCA) scenarios from TYNDP 2018 respectively.

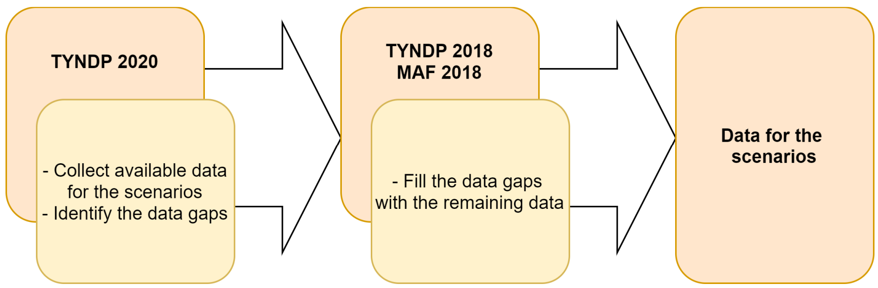
Assuming these as the main data sources, and taking into consideration that the goal of FlexPlan is to create three different scenarios for each one of the three considered target years, it is therefore natural that the FlexPlan scenarios are as similar as possible to those presented by ENTSOs in the TYNDP 2020 study. Using this approach, FlexPlan reduces the need for basic/fundamental scenario data validation, as the scenarios created are based on already validated data. Thus, FlexPlan scenarios are:

- National Trends (NT) – 2030;
- National Trends (NT) – 2040;
- National Trends (NT) – 2050;
- Distributed Energy (DE) – 2030;
- Distributed Energy (DE) – 2040;
- Distributed Energy (DE) – 2050;
- Global Ambition (GA) – 2030;
- Global Ambition (GA) – 2040;
- Global Ambition (GA) – 2050.

2.2 Methodology to obtain scenarios data

The data for the scenarios is taken mainly from the Scenario Data Sets in TYNDP 2020, provided by ENTSO-E. If some of the data is not available in TYNDP 2020, the data from TYNDP 2018 and Mid-term Adequacy Forecast (MAF) 2018 is used to fill these gaps. Figure 2-1 shows the steps of collecting data for the scenarios, considered in FlexPlan project.

Figure 2-1 - The steps of collecting data for the scenarios and the sources of the data.



The data, which is obtained from TYNDP 2020, TYNDP 2018 and MAF 2018, is an input for the MILES software. To calculate the data on the regional level, MILES needs to have the input data for installed generation capacities, energy consumption for the target years as well as historical time series of the load and information on cross-border capacities between European countries. Also the prices for the fuel are needed for the market simulation module of MILES.

For the well-established existing pan-European scenarios up to 2050 the publicly available data with regard to the potential development of the power systems have been summarized in 7 topics:

- Installed generation capacities by technology (as indicated in section 2.2.1);
- Annual mean capacity factors for renewable energy sources;
- Annual electricity consumption and peak load;
- Hourly time series data for consumption;
- Net transfer capacities;
- Commodity prices for different types of fuel for nuclear and fossil power station;
- Total operational reserve power.

Therefore, each scenario corresponds to a set of these data. FlexPlan aims to create nine scenarios describing the pan-European power system up to 2050. While for 2030 and 2040, the TYNDP studies can be used as main data sources as they already provide data at national level or these target years, in 2050 a different methodology was created to collect and validate data at national and pan-European level. The next two sections describe the two methodologies used to create the 2030, 2040 and 2050 FlexPlan scenarios.

2.2.1 2030 and 2040 Scenarios Data

This section describes the used methodology to collect data from TYNDP 2020 (and complemented by data from TYNDP 2018) and convert these data into the aforementioned seven topics, which are the direct data inputs to be used by the MILES software, allowing to perform the pan-European simulations and the creation of target scenarios to be considered by the different regional cases.

1. Installed generation capacities.

One of the required inputs for MILES, and one of the most important for power system simulations, corresponds to the installed capacity for energy generation. MILES uses an extensive list, separating installed capacities into different categories. Although TYNDP 2020 is used as the main data source, it is complemented by TYNDP 2018, when there is no data directly available. This is the case of the considered technologies: "biomass" and "other RES". MILES requires that these are taken separately, but TYNDP 2020 only provides a single value for these technologies. Thus, and since TYNDP 2018 separated these technologies in a similar way to MILES requirements, it is also used to calculate the share of each one of these two installed capacities. Table 2-1 includes the set of installed capacities used as MILES inputs, together with the corresponding technologies used as data sources in TYNDP 2020 and TYNDP 2018. TYNDP 2018 technologies are only displayed in the cases where it was necessary to resort to this data source.

	Input data for MILES Software	TYNDP 2020	TYNDP 2018
	Nuclear Power	Nuclear	
Fossil Fuels	Lignite	Lignite	
	Hard Coal	Hard coal	
	Oil	Heavy Oil	
		Light Oil	
		Oil shale	
	Natural gas	Natural gas	
	Other fossil fuels	Other non-RES	
	Mixed Fuels	-	
Renewable Energy Sources (other than Hydro)	Wind onshore	Wind onshore	
	Wind offshore	Wind offshore	
	Solar	Solar Thermal	
		Solar PV	
	Biomass	Other RES	Biomass
	Other RES		Other RES
Hydro power	Run-of-river Hydro Power Plant (HPP)	Run-of-river HPP	
	Storage HPP	Reservoir	
	Pumped storage HPP	Pump storage closed	
		Pump storage open	
	Battery	Battery	
	Demand Side Response (DSR)	Demand Side Response (DSR)	
	Power-to-gas (P2G)	Power-to-gas (P2G)	

Table 2-1 - Types of installed generation capacities.

From Table 2-1 it can be seen that most of the data can be taken directly from TYNDP 2020, as there is a direct relation between TYNDP 2020 and MILES input categories for installed capacity. However, some of the data must be calculated taking into account the share of types of generation capacities from TYNDP 2018 using the sum of generation capacities from TYNDP 2020 as the aforementioned case of biomass + other RES. As an illustrative example, the Distributed Energy scenario for 2030 for Germany is further considered, since there is a variety of types of installed generation capacities. This data is presented in Table 2-2.

Input data for MILES Software	TYNDP 2020	TYNDP 2018
Nuclear Power	0	
Fossil Fuels	-	
Lignite	7 678	
Hard Coal	6 604	
Oil	840	
Natural gas	22 135	
Other fossil fuels	15 810	
Mixed Fuels	-	
Renewable Energy Sources (other than Hydro)	-	
Wind	-	
Wind onshore	95 501	
Wind offshore	17 340	
Solar	109 876	
Biomass	6 635	0
Other RES		6 631
Hydro power (total)	-	
Run of river HPP	4 036	
Storage HPP	1 297	
Pumped storage HPP	10 037	
Battery	5 060	
Demand Side Response (DSR)	5 888	
Power-to-gas (P2G)	2 000	

Table 2-2 - Generation capacities for Germany in Distributed Energy scenario in 2030 (both TYNDPs).

The methodology to filling the input data for MILES software is as follows:

a. Nuclear power, Natural gas, Hard coal, Lignite, Wind onshore, Wind offshore, Battery, DSR, P2G and Peak: the installed generation capacities are taken directly from TYNDP 2020;

b. Other fossil fuels: the installed generation capacities are taken directly from Other non-RES in TYNDP 2020. These capacities represent small-scale CHPs, which are mainly driven by oil, lignite, coal, natural and decarbonised gas in 2030. In order to follow the thermal phase-out storylines, the share of oil, lignite, coal and natural gas (which are considered as fossil fuels) is taken 90% in 2030, 50% in 2040 and 10% in 2050. The remaining installed capacity is decarbonised gas, which is considered to be both non-RES and non-fossil fuel source of generation;

c. Oil: value is calculated as the sum of the three technologies considered in TYNDP2020 (light, heavy and oil shale);

d. Solar: value is calculated as the sum of the two technologies considered in TYNDP2020 (PV and solar thermal);

e. Biomass and other RES: values are calculated in accordance with share in TYNDP 2018, this calculation is presented in Table 2-3.

Calculation Steps	**Biomass [MW] or %**	**Other RES [MW] or %**	**Sum of Biomass + Other RES [MW]**	**Source**	**Step Description/ Comment**
1	0	6631	**6631**	TYNDP 2018	Data from TYNDP 2018

2	0%	100%			Calculate Percentage
3			**6635**	TYNDP 2020	Data from TYNDP 2020
4	**0**	**6635**			Adjust according percentage

Table 2-3 - Calculation of Biomass/Other RES share for input data for MILES for DE scenario in 2030 in Germany.

f. Fossil Fuels: values are calculated as a sum of Lignite, Hard coal, Oil, Natural gas, Other fossil fuels and Mixed fuels.

g. Wind: values are calculated as a sum of Wind onshore and wind offshore.

h. Renewable Energy Sources (other than Hydro): values are calculated as a sum of Wind, Solar, Biomass and other RES.

Table 2-4 includes the values of the generation capacity in Germany in Distributed Energy scenario for 2030, created using the aforementioned methodology and ultimately used for MILES input.

Input data for MILES Software	Installed generation capacity [MW]
Nuclear Power	0
Fossil Fuels	51 485
Lignite	7 678
Hard Coal	6 604
Oil	840
Natural gas	22 135
Other fossil fuels	15 810
Mixed Fuels	0
Renewable Energy Sources (other than Hydro)	212 012
Wind	112 841
Wind onshore	95 501
Wind offshore	17 340
Solar	109 876
Biomass	0
Other RES	6 635
Hydro power (total)	15 370
Run of river HPP	4 036
Storage HPP	1 297
Pumped storage HPP	10 037
Battery	5 060
Demand Side Response (DSR)	5 888
Power-to-gas (P2G)	2 000

Table 2-4 - Generation capacities for Germany in Distributed Energy scenario in 2030.

2. Annual mean capacity factors for renewable energy sources

The annual mean capacity factors for Wind, Solar, Biomass, Hydro generation and for other RES are calculated from installed generation capacities for these types of generation and annual energy generation, provided by TYNDP 2020, using the formula:

$$Annual\ RES\ Capacity\ Factor = \frac{Annual\ Energy\ Generation\ [GWh] \cdot 1000}{Installed\ Generation\ Capacity\ [MW] \cdot 8760} \cdot 100\%$$

The values for Biomass and Other RES will be equal because the data for Biomass and Other RES in TYNDP 2020 is summarized. Thereby, Table 2-5 includes the values for Germany in Distributed Energy scenario in 2030.

Type of the generation	Description	Values
Wind	Capacity [MW]	112 841

	Generation [GWh]	287 674
	Annual RES capacity factor [%]	29.1
Solar	Capacity [MW]	109 876
	Generation [GWh]	106 939
	Annual RES capacity factor [%]	11.1
Biomass + Other RES	Capacity [MW]	6 635
	Generation [GWh]	37 884
	Annual RES capacity factor [%]	65.2
Hydro	Capacity [MW]	15 370
	Generation [GWh]	30 793
	Annual RES capacity factor [%]	22.9

Table 2-5 - Annual mean capacity factors for Germany in Distributed Energy scenario in 2030.

3. Annual electricity consumption and peak load

Annual electricity consumption and peak load are taken directly from TYNDP 2020. For Germany in Distributed Energy scenario in 2030 they are 688 TWh and 101.570 GW respectively. It is important to note that the climate year 1984 is taken for the consumption and load in TYNDP.

4. Hourly time series data for consumption

The data for hourly time series for consumption is taken from TYNDP 2018 due to absence of this information in TYNDP 2020. However, the MILES software needs only the behavior of the consumption throughout the day and uses annual electricity consumption to calculate the new hourly time series data for consumption, thus this data is sufficient to be used as input.

5. Net transfer capacities

The data for net transfer capacities (NTC) is taken from TYNDP 2020. The complete information for NTC's is given in Appendix B.

6. Commodity prices for different types of fuel for nuclear and fossil power station

The data for commodity prices for different types of fuel is taken directly from TYNDP 2020, as illustrated in Table 2-6. TYNDP considers the same commodity prices for the three scenarios, thus we also employ this strategy.

	Price	2020	2021	2023	2025		2030			2040			2050		
					BE	G2C	NT	DE	GA	NT	DE	GA	NT	DE	GA
Nuclear	€/GJ	0.47	0.47	0.47	0.47		0.47			0.47			0.47		
Lignite		1.1	1.1	1.1	1.1		1.1			1.1			1.1		
Oil shale		2.3	2.3	2.3	2.3		2.3			2.3			2.3		
Hard coal		3.0	3.12	3.4	3.79		4.3			6.91			9.52		
Natural gas		5.6	5.8	6.1	6.46		6.91			7.31			7.71		
Light Oil		12.9	14.1	16.4	18.8		20.5			22.2			23.9		
Heavy Oil		10.6	11.1	12.2	13.3		14.6			17.2			19.8		
CO_2 Price	€/tCO_2	19.7	20.4	21.7	23	56	27	53	35	75	100	80	123	147	125

Table 2-6 – Commodity prices (source: TYNDP2020).

7. Total operational reserve power

The values for reserves (FCR and FRR) are calculated from the data, obtained in "Installed generation capacities by type" table and "Annual electricity consumption and peak load" table. This reserve is split in Frequency Containment Reserve (FCR) and Frequency Restoration Reserve (FRR). FCR is calculated for three zones: Continental Europe, Nordic countries and UK with Ireland. Countries in Continental Europe must contribute to FCR in percentage of their Generation Energy, which is provided by TYNDP 2020. The volume of FCR for Continental Europe is 3000 MW [6]. It is important to note, that by 2030 Baltic countries will be part of Continental Europe Grid so they will participate in FCR and FRR for Continental Europe zone as well. Nordic countries (Denmark East, Finland, Norway and Sweden) have their own regulations for FCR. The volume of FCR in Nordic countries zone is 1000 MW and split between countries in percentage of their Peak Load power [7]. The volume of FCR for United Kingdom and Ireland is 1500 MW and split between these countries in percentage of Generation Energy [8].

FRR is calculated by the different TSOs and reported by ENTSO-E in MAF 2018 [9]. In this report, the values for sum of FCR and FRR are calculated for all European countries in accordance of their peak load and installed capacities. Using the data obtained in "Annual electricity consumption and peak load" table, the value of sum of FCR and FRR can be calculated in accordance of the peak load in considered scenario and FRR can be calculated as a subtraction of FCR from the total value.

2.2.2 2050 Scenarios Data

Due to the absence of the data for 2050 in TYNDP 2018, TYNDP 2020 and MAF 2018, it was necessary to create a different methodology to obtain the corresponding scenarios for this target year. The used methodology consist of two main steps:

- Following trends demonstrated in TYNDP 2020 – using a linear approach from the values already given for 2030 and 2040, but following a set of rules demonstrated below;
- Validation of obtained results using a well know data source with already validated scenarios for 2050 – **A Clean Planet for all** strategy by the European Commission [10].

In the first step, data calculation for 2050 was performed using linear approximation of data from 2030 and 2040 with some exceptions:

- "Installed generation capacities" table:
    - If the data for 2050 due to linear approximation goes to negative values, it is considered to be 0 in 2050;
    - If the data for Gas, Nuclear or Other Fossil fuels increases from 2040 to 2050, the value in 2050 is considered to be the same as in 2040;
    - If the data for Biomass or Other RES decreases from 2040 to 2050, the value in 2050 is considered to be the same as in 2040;
- "Annual mean capacity factors for renewable energy sources" table:
    - The linear approximation applies only to Annual energy generation and Installed generation capacity, the capacity factor is calculated using the same methodology as in Chapter 2.2.1;

- If the data for Biomass or Other RES decreases from 2040 to 2050, the value in 2050 is considered to be the same as in 2040;

- "Total operational reserve power" table:
  - The linear approximation applies only to Generation energy and peak load power, the reserves are calculated using the same methodology as in Chapter 2.2.1 with the same volumes of FCR (3000 MW for Continental Europe, 1000 for Nordic countries and 1500MW for United Kingdom and Ireland) and the same calculation for FRR, which is calculated using MAF 2018 as the main source of the data for FRR;
  - If the data for generation energy decreases from 2040 to 2050, the value in 2050 is considered to be the same as in 2040.

The results of the first step of calculations for the pan-European level are presented in Table 2-7.

Description	Installed generation capacity [MW] for scenarios		
	NT - 2050	DE - 2050	GA - 2050
Nuclear Power	65 729.4	69 461	62 364
Fossil Fuels	273 494.3	267 409.2	273 318
Lignite	13 079.9	7 717.2	7 716
Hard Coal	12 467.6	11 720.6	17 686
Oil	1 936.3	1 936.3	1 936
Natural gas	182 458.7	182 458.7	182 436
Other fossil fuels	63 551.9	63 551.9	63 551.9
Mixed Fuels	0	0	0
Renewable Energy Sources (other than Hydro)	1 283 095.1	1 961 924.6	1 263 931
Wind	644 631.4	847 438.5	690 999
Wind onshore	461 507.6	746 005.7	486 903
Wind offshore	183 123.8	101 432.8	204 096
Solar	598 617.2	1 020 789	534 608
Biomass	1 420.6	1 467.7	1 445.2
Other RES	38 426	38 378.9	36 878.8
Hydro power (total)	239 381.5	239 381.5	239 372
Run of river HPP	56 531.8	56 531.8	56 529
Storage HPP	77 397.4	77 397.4	77 395
Pumped storage HPP	105 452.3	105 452.3	105 448
Battery	109 028.7	198 090.3	61 639
Demand Side Response (DSR)	34 389.2	49 096.2	49 092
Power-to-gas (P2G)	5 025	5 025	2 000

Table 2-7 - The installed capacity data for Europe for 2050 (first step).

These results for 2050 are then compared with the "Clean Planet for all" report, which can be considered as the main source of the information for 2050 data [10]. This report has a European long-term strategic vision for a prosperous, modern, competitive and climatic neutral economy and set the European Union on the ambitious decarbonisation trajectory that was set out with the Paris Agreement. The "Clean Planet for all" report has 9 different scenarios:

- **Baseline** – this scenario reflects the current EU decarbonisation trajectory based largely on agreed EU policies, or policies that have been proposed by the Commission but are still under discussion in the European Parliament and Council;
- Scenarios aiming at 80 % reduction of GHG emissions in 2050 (compared to 1990):
  - **EE** – Focused on energy efficiency; strategies
  - **CIRC** – focused on circular economy related solutions;

    - Scenarios driven by decarbonized energy carriers:
        - **ELEC** – electricity;
        - **H2** – hydrogen;
        - **P2X** – e-fuels;
- **COMBO** - this scenario serves as a bridge between the category EE/CIRC and ELEC/H2/P2X
- Scenarios aiming at net zero GHG emissions by:
    - **1.5TECH** –aims to further increase the contribution of all the technology options, and relies more heavily on the deployment of biomass associated with significant amounts of carbon capture and storage;
    - **1.5LIFE** – relies less on the technology options of 1.5TECH, but assumes a drive by EU business and consumption patterns towards a more circular economy.

FlexPlan scenarios for 2050 must be in line with the EU decarbonisation trajectory based on the EU policies and "Clean Planet for all" report scenarios. In this case, the National Trends (NT) scenario will be compared with ELEC scenario, Distributed Energy (DE) and Global Ambition (GA) scenarios will be compared with the European Commission's most ambitious 1.5TECH and 1.5LIFE scenarios (average), following the same strategy already mentioned by ENTSO-E in the methodological report for the creation of these scenarios [4].

According to the "Clean Planet for all" report, wind capacity in 2050 is between 700 GW (EE) and 1200 GW (P2X) in scenarios achieving 80 % GHG reduction and 1.5TECH scenario goes slightly higher to over 1200 GW. The solar capacity in 2050 is between 500 GW (EE) and 970 GW (P2X) for scenarios achieving 80% GHG reduction and up to some 1000 GW in the 1.5TECH scenario. The biomass and other RES capacity grows up to 83 GW (P2X) in 2050. The gas-fired capacities in 2050 is between 141 GW (P2X) and 226 GW (ELEC) in scenarios achieving 80% GHG reductions and decreasing up to 100 GW in the 1.5LIFE scenario, compared to 2015. The coal-fired capacities progressively get out of the power mix in 2050. The oil-fired capacities virtually disappear already in 2030, with less than 5 GW still installed in all scenarios, which are used either in specific applications in industry or serving reserve purposes.

Comparing these values of installed generation capacities and the ranges of these capacities, the second step of the data calculation for 2050 was performed with new exceptions:

- Lignite and Hard coal capacities are set to 0 to be in line with target of net-zero EU-28 emissions by 2050 in all scenarios, being redistributed to wind and solar as a percentage of 50%/50%;
- Gas capacities are reduced by 50% in DE and GA scenarios to be in line with 1.5TECH and 1.5LIFE, being redistributed to wind and solar as a percentage of 50%/50%.

The results of the second step of calculations are presented in Table 2-8.

Description	Installed generation capacity [MW] for scenarios		
	NT – 2050	DE - 2050	GA - 2050
Nuclear Power	65 729.4	69 461.0	62 364
Fossil Fuels	247 946.8	156 717.5	156 698
Lignite	0	0	0
Hard Coal	0	0	0
Oil	1 936.3	1 936.3	1 936
Natural gas	182 458.7	91 229.3	91 218
Other fossil fuels	63 551.9	63 551.9	63 551.9

Mixed Fuels	0	0	0
Renewable Energy Sources (other than Hydro)	1 308 642.6	2 018 741.2	1 388 198
Wind	657 405.2	902 772.1	752 375.5
Wind onshore	471 357.3	792 159.7	531 323
Wind offshore	186 047.9	110 612.3	221 052.6
Solar	611 390.9	1 076 122.6	595 984.5
Biomass	1 420.5	1 467.7	1 445.2
Other RES	38 426.0	38 378.9	36 878.8
Hydro power (total)	239 381.5	239 381.5	239 372
Run of river HPP	56 531.8	56 531.8	56 529
Storage HPP	77 397.4	77 397.4	77 395
Pumped storage HPP	105 452.3	105 452.3	105 448
Battery	109 028.7	198 090.3	61 639
Demand Side Response (DSR)	34 389.2	49 096.2	49 092
Power-to-gas (P2G)	5 025.0	5 025.0	2 000

Table 2-8 - The installed capacity data for Europe for 2050 (second step).

A comparison of data obtained after this process is depicted in Figure 2-2. Comparing these results with “Clean Planet for all” report, it can be said that the data for installed generation capacities in FlexPlan are in line with current EU decarbonisation trajectory based largely on agreed EU policies and the Paris Agreement.

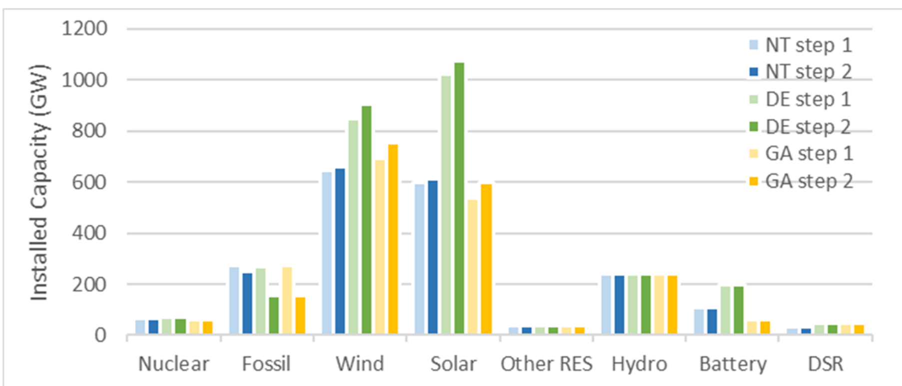


Figure 2-2 – FlexPlan Scenarios data for 2050 – intermediate step and final installed capacities comparison.

2.3 Scenario: National Trends

The analysis of the National Trends scenario in target years (2030-2040-2050) is presented in this section. As some indicative figures for the illustration of the obtained results, this section contains an analysis of the evolution of installed capacity (by technology) for the three target years at European level. Additionally, different countries are used as examples to showcase the main characteristics of the scenario, in terms of load variation (peak load and total consumption) and FCR changes. Figure 2-3 and

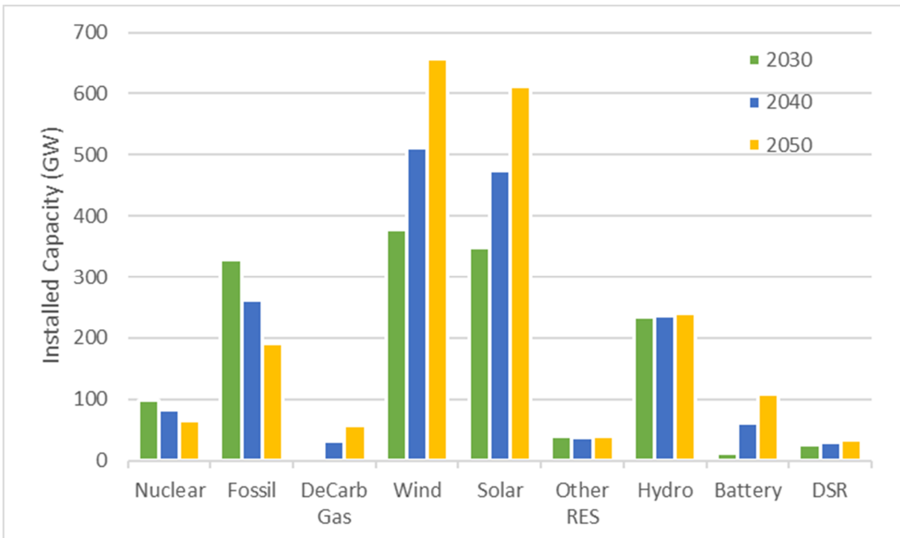


Figure 2-3 - National Trends scenario installed capacity at EU level: evolution from 2030 to 2050.

Figure 2-4 depict the evolution of installed capacity at European level, from 2030 to 2050.

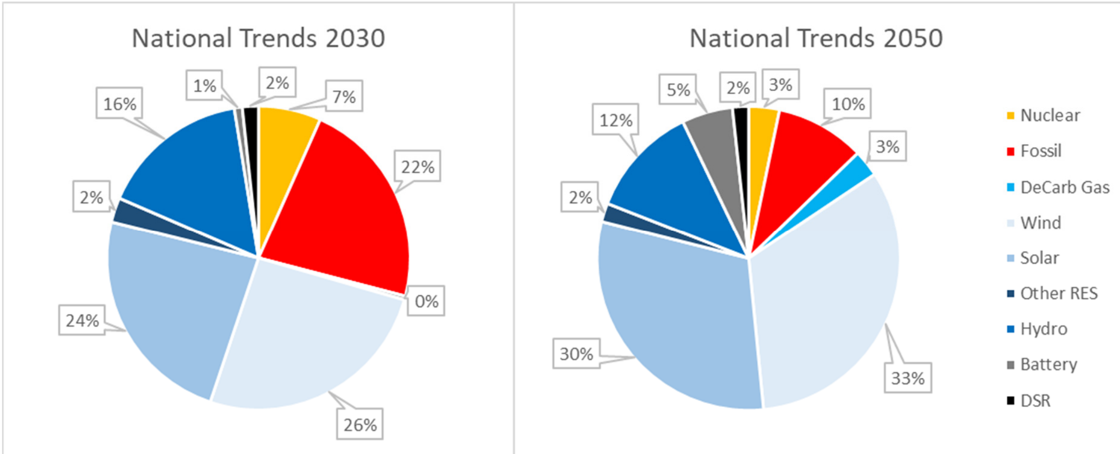


Figure 2-4 - National Trends scenario installed capacities shares at EU level: evolution from 2030 to 2050.

The total installed capacity increases from 1472 GW to 2010 GW in this period, corresponding to an increase of 36.6 %. The share of non-RES (nuclear and fossil) decreases from 29% in 2030 to 13% in 2050, thus demonstrating the clear transition for RES solutions. The shares of wind and solar energy sources increase from 26% to 33% and 24% to 30% respectively. It is important to note, that the installed generation for P2G is not shown, because its share is less than 0.3% for all the target years.

The annual electricity consumption increases from 3515 TWh in 2030 to 4309 TWh in 2050. The largest increase in electricity consumption in percentage will be in Latvia (+77.9%), Western Denmark (+55.4%) and Greece (+48.5%), the largest increase in electricity consumption in absolute values will be in Germany (+166 TWh). The peak load increases from 595 GW in 2030 to 720 GW in 2050, the largest increase in peak load in percentage will be in Latvia (+159.4%), the largest increase in peak load in absolute values will be in Spain (+22.5 GW).

In order to illustrate the evolution of installed capacities at country level, four countries are considered as examples. Thus, changes of the share of different types of generation in Germany, Montenegro, Norway and Spain from 2030 to 2050 are presented in Figure 2-5, Figure 2-6, Figure 2-7 and Figure 2-8.

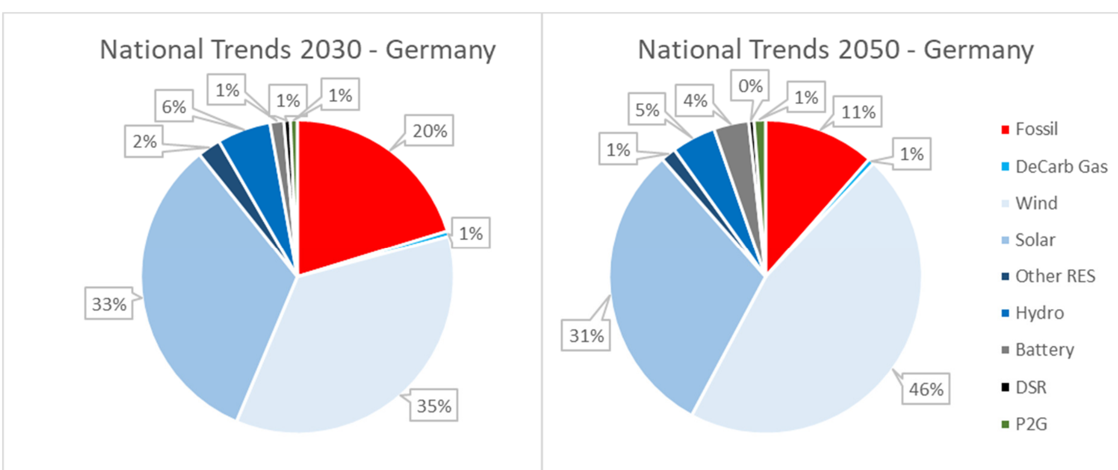


Figure 2-5 - The installed generation capacity in National Trends scenario in Germany in 2030 and 2050.

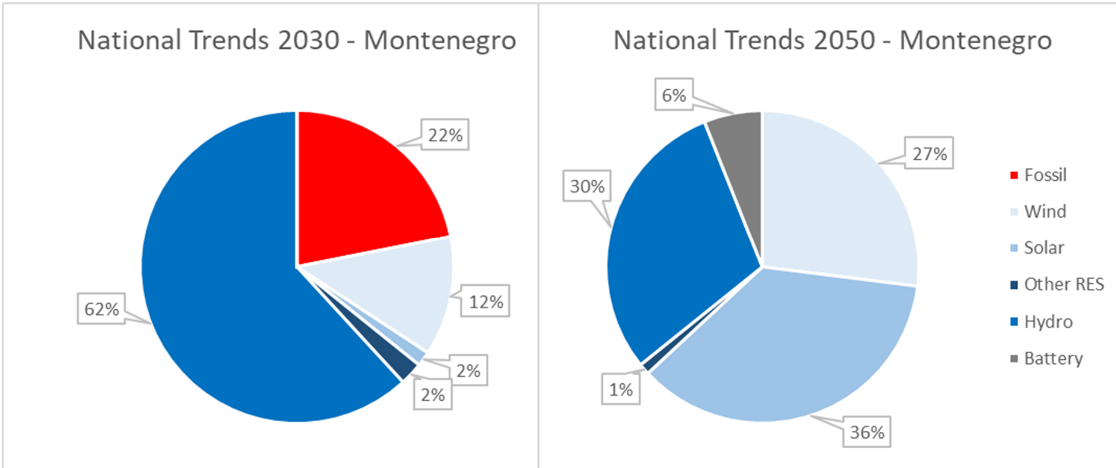


Figure 2-6 - The installed generation capacity in National Trends scenario in Montenegro in 2030 and 2050.

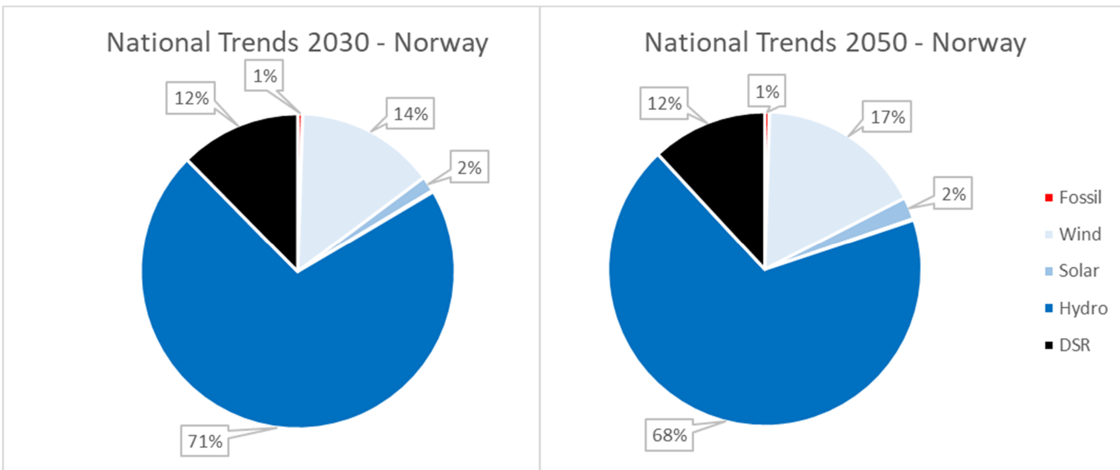


Figure 2-7 - The installed generation capacity in National Trends scenario in Norway in 2030 and 2050.

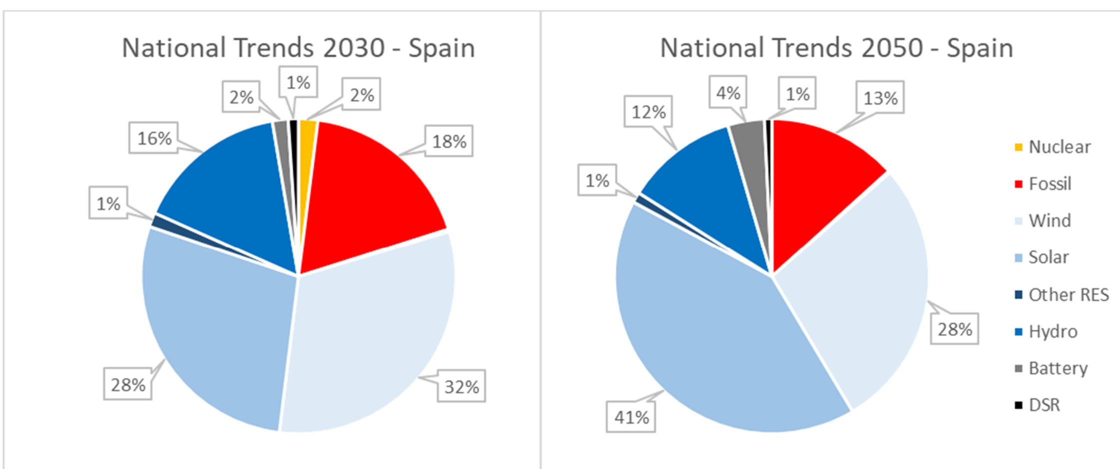


Figure 2-8 - The installed generation capacity in National Trends scenario in Spain in 2030 and 2050.

From these figures it can be seen that in Germany, taking into account the increase in installed generation capacity, the biggest increase is taken by wind generation (from 35% in 2030 to 46% in 2050), Montenegro will not have fossil fuel generation in 2050 with a significant increase in wind (from 12% in 2030 to 27% in 2050) and solar (from 2% in 2030 to 36% in 2050). Although hydro reduces the share from 62% to 30% in fact the installed capacity for this technology does not change during this period. The reduction of share is due to the increase of the total installed capacity. Norway will have mainly hydro generation (from 71% in 2030 to 68% in 2050, which also reflects not the decrease of hydro generation capacity, but increase the share of wind). Spain will have the biggest increase in solar generation capacity (from 28% in 2030 to 41% in 2050).

The changes of the peak load, installed capacity and total demand in these countries in target years 2030-2040-2050 are presented in Figure 2-9, Figure 2-10, Figure 2-11, Figure 2-12.

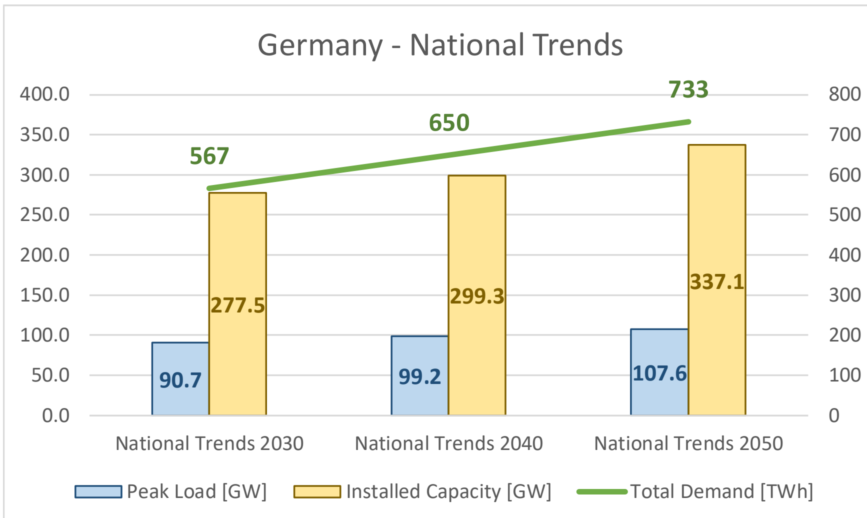


Figure 2-9 - The change of peak load, installed capacity and total demand in Germany in National Trends scenario.

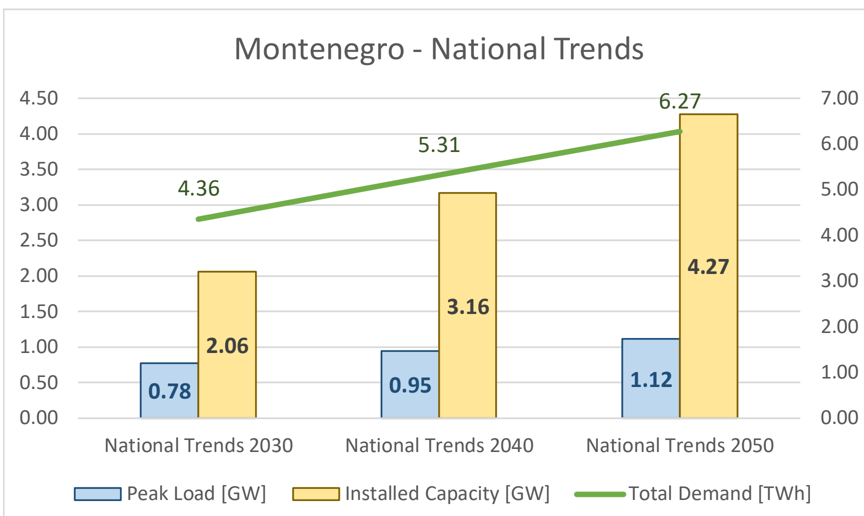


Figure 2-10 - The change of peak load, installed capacity and total demand in Montenegro in National Trends scenario.

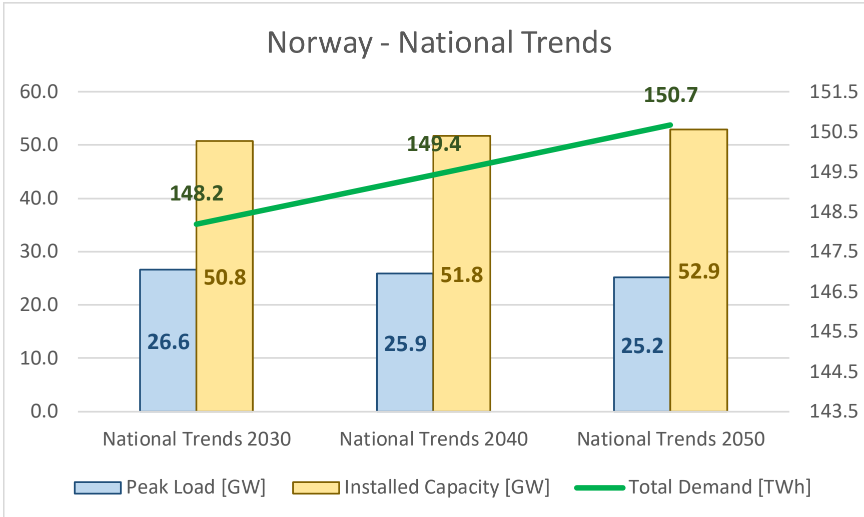


Figure 2-11 - The change of peak load, installed capacity and total demand in Norway in National Trends scenario.

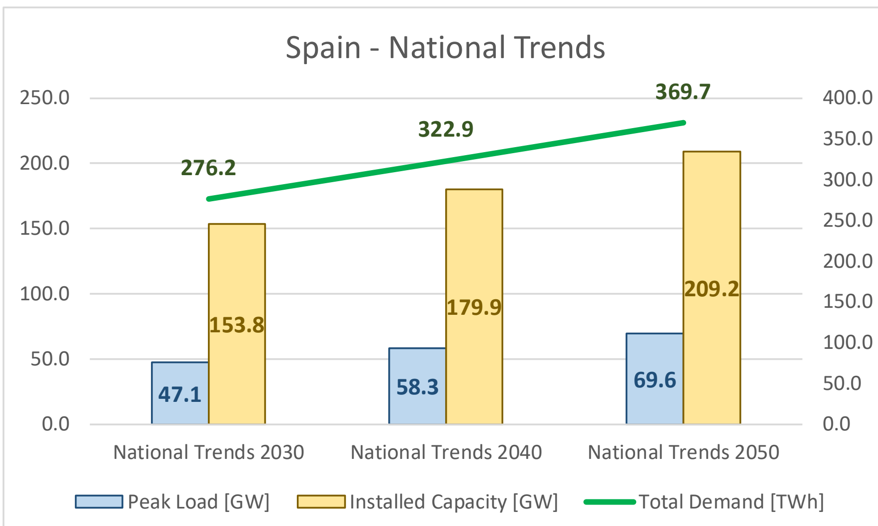


Figure 2-12 - The change of peak load, installed capacity and total demand in Spain in National Trends scenario.

The reserves remain the same in 2050, when compared to 2030, which are 3000 MW for Continental Europe zone, 1000 MW for Nordic countries zone and 1500 MW in United Kingdom and Ireland. The largest increase in FCR reserve is expected to be in Portugal (from 52.5 MW in 2030 to 95.8 MW in 2050), while the largest increase in FRR reserve is expected to be in Turkey (from 2409 MW in 2030 to 3794 MW in 2050).

2.4 Scenario: Distributed Energy

The analysis of the Distributed Energy scenario in target years (2030-2040-2050) is presented in this chapter. Figure 2-13 and Figure 2-14 show the evolution of installed generation capacity in Europe in this scenario.

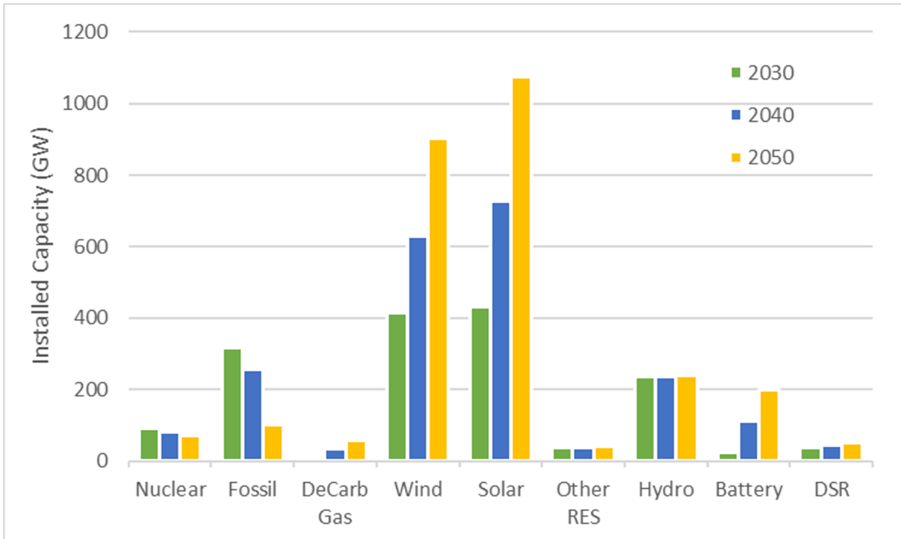


Figure 2-13 - Distributed Energy scenario installed capacity at EU level: evolution from 2030 to 2050.

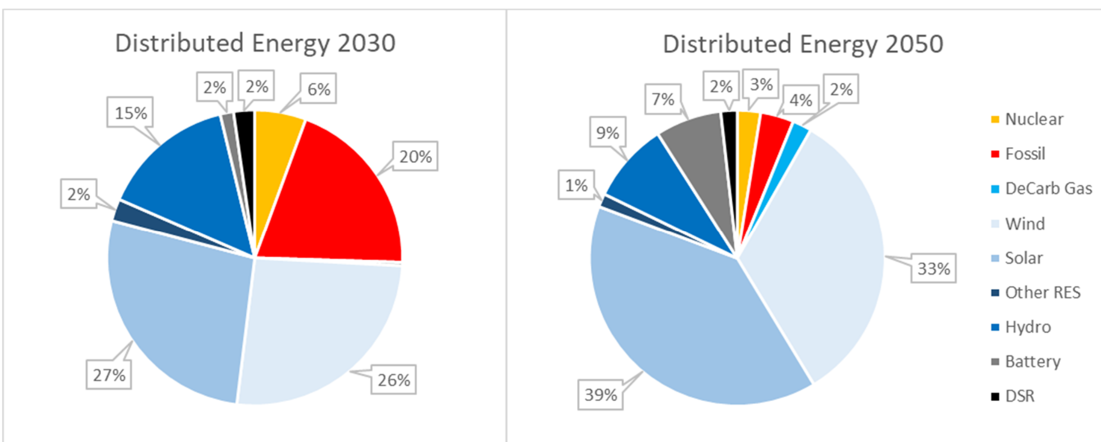


Figure 2-14 - Distributed Energy scenario installed capacities shares at EU level: evolution from 2030 to 2050.

In Distributed Energy, the total installed capacity increases from 1596 GW to 2736 GW in this period, corresponding to an increase of 71.4 %. The share of non-renewable energy sources (nuclear and fossil) decrease from 26% in 2030 to 7% in 2050. The shares of wind and solar energy sources increase from 26% to 33% and 27% to 39% respectively. It is important to note, that the installed generation for P2G resources is not shown, because its share is less than 0.2% for all the target years.

The annual electricity consumption increases from 3783 TWh in 2030 to 5048 TWh in 2050. The largest increase in electricity consumption in percentage will be in Latvia (+77.9%), Eastern Denmark (+77.8%) and Finland (+70.7%), the largest increase in electricity consumption in absolute values will be in Germany (+218 TWh). The peak load increases from 611 GW in 2030 to 810 GW in 2050, the largest increase in peak load in percentage will be in Romania (+114.4%), the largest increase in peak load in absolute values will be in Germany (+43.4 GW).

The changes of the share of different types of generation in Germany, Montenegro, Norway and Spain from 2030 to 2050 are presented in Figure 2-15, Figure 2-16, Figure 2-17 and Figure 2-18.

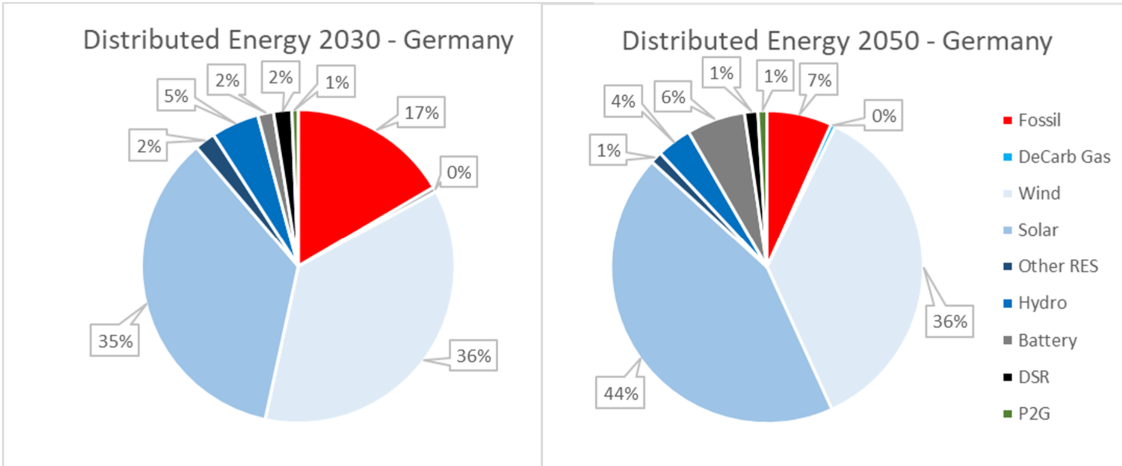


Figure 2-15 - The installed generation capacity in Distributed Energy scenario in Germany in 2030 and 2050.

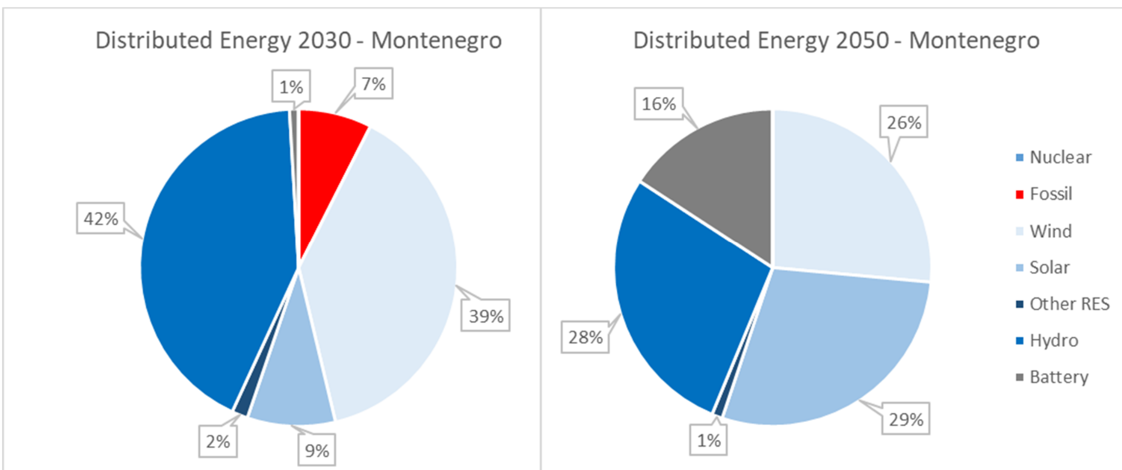


Figure 2-16 - The installed generation capacity in Distributed Energy scenario in Montenegro in 2030 and 2050.

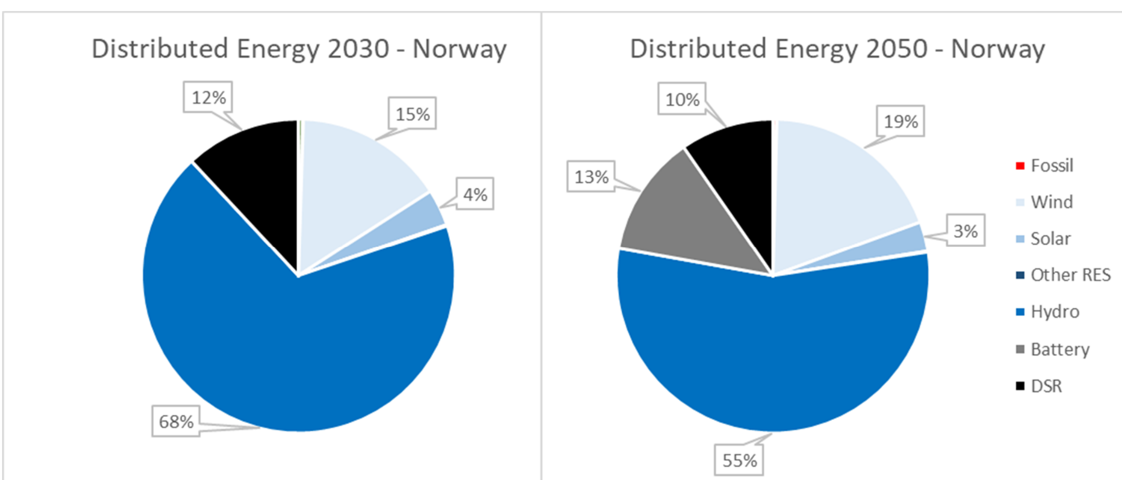


Figure 2-17 - The installed generation capacity in Distributed Energy scenario in Norway in 2030 and 2050.

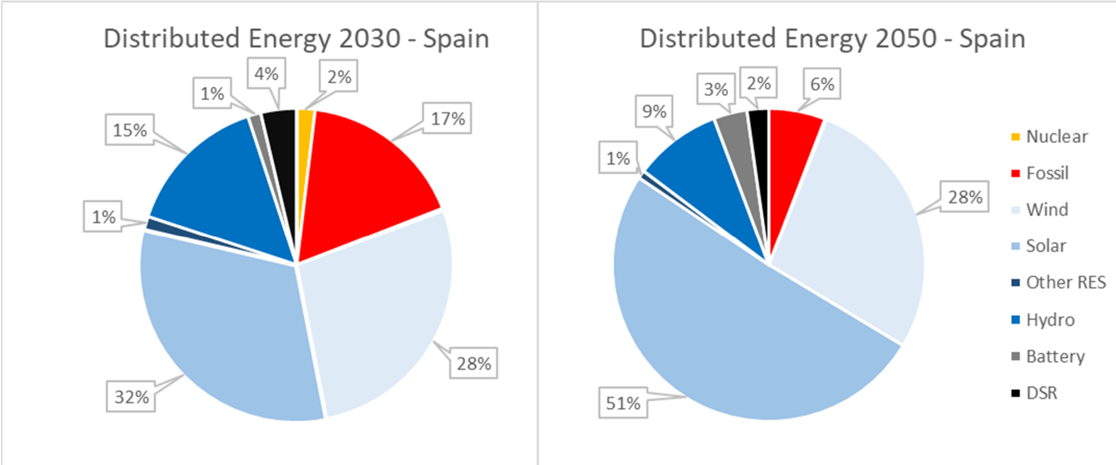


Figure 2-18 - The installed generation capacity in Distributed Energy scenario in Spain in 2030 and 2050.

The changes of the peak load, installed capacity and total demand in these countries in target years 2030-2040-2050 are presented in Figure 2-19, Figure 2-20, Figure 2-21 and Figure 2-22.

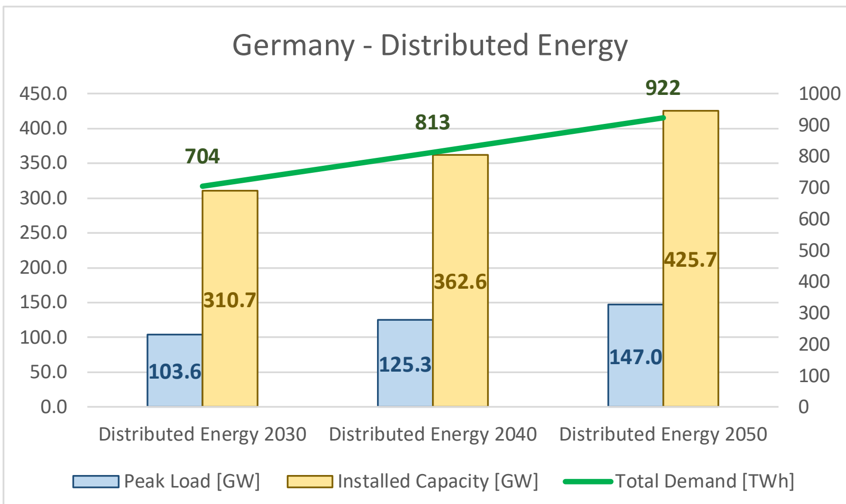


Figure 2-19 - The change of peak load, installed capacity and total demand in Germany in Distributed Energy scenario.

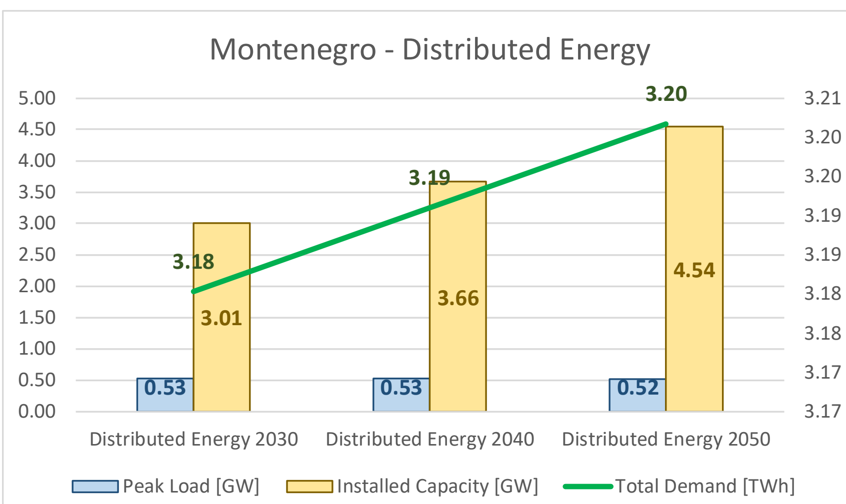


Figure 2-20 - The change of peak load, installed capacity and total demand in Montenegro in Distributed Energy scenario.

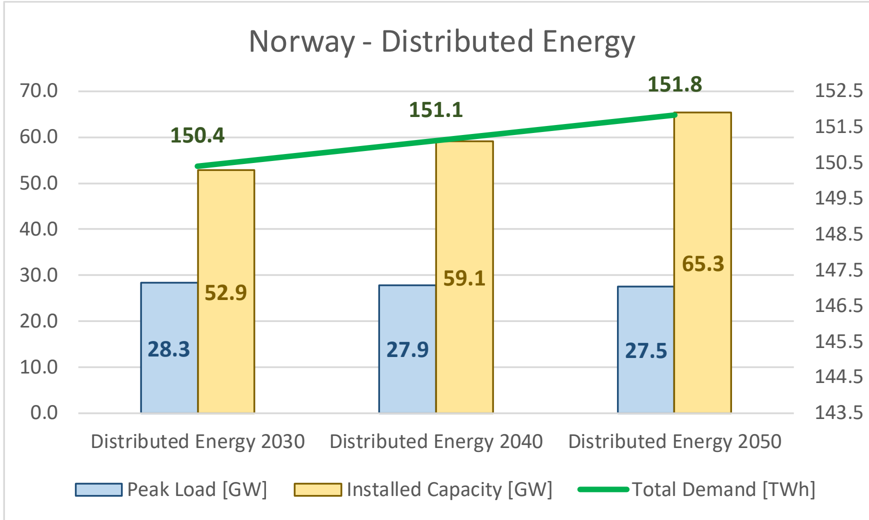


Figure 2-21 - The change of peak load, installed capacity and total demand in Norway in Distributed Energy scenario.

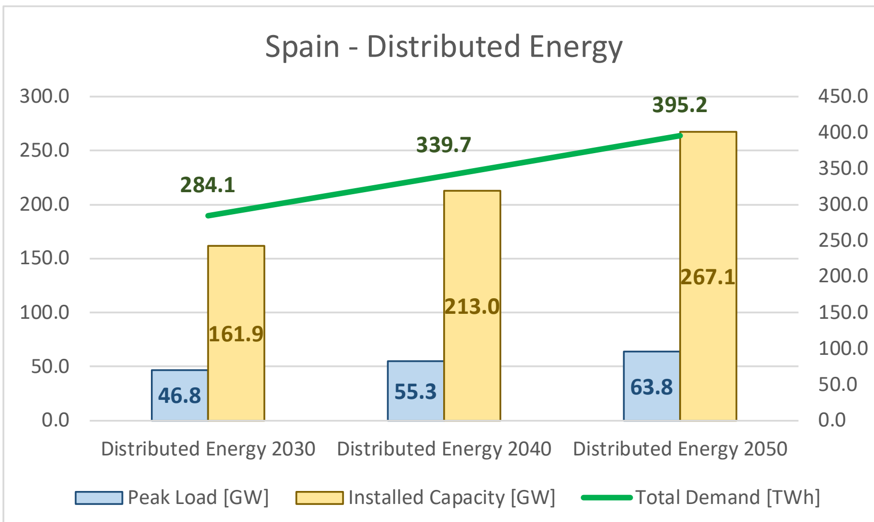


Figure 2-22 - The change of peak load, installed capacity and total demand in Spain in Distributed Energy scenario.

From these figures it can be seen, that in Germany, taking into account the increase in installed generation capacity, the biggest increase is taken by solar generation (from 35% in 2030 to 44% in 2050), Montenegro will not have fossil fuel generation in 2050 with large increase in solar (from 9% in 2030 to 29% in 2050) and battery (from 1% in 2030 to 16% in 2050) generation capacity, Norway will have mainly hydro generation (from 68% in 2030 to 55% in 2050, which reflects not the decrease of hydro generation capacity, but increase the share of wind and batteries), Spain will have the biggest increase in solar generation capacity (from 32% in 2030 to 51% in 2050).

The reserves remain the same in 2050, which are 3000 MW for Continental Europe zone, 1000 MW for Nordic countries zone and 1500 MW in United Kingdom and Ireland. The largest increase in FCR and FRR reserves will be in Turkey (from 356 MW in 2030 to 432.8 MW in 2050 and from 2839 MW in 2030 to 5015 MW in 2050 respectively).

2.5 Scenario: Global Ambition

The analysis of the Global Ambition scenario in target years (2030-2040-2050) is presented in this chapter. Figure 2-23 and Figure 2-24 show the evolution of installed generation power in Europe.

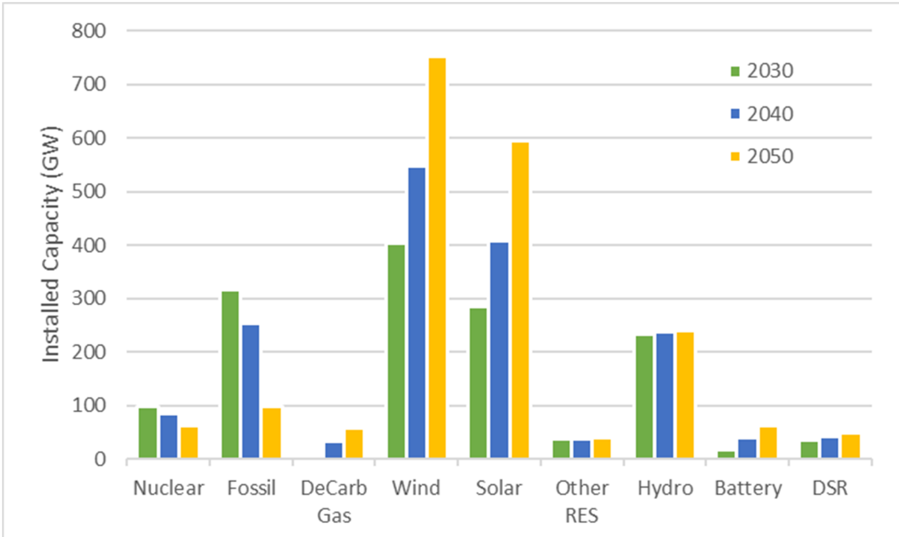


Figure 2-23 - Global Ambition scenario installed capacity at EU level: evolution from 2030 to 2050.

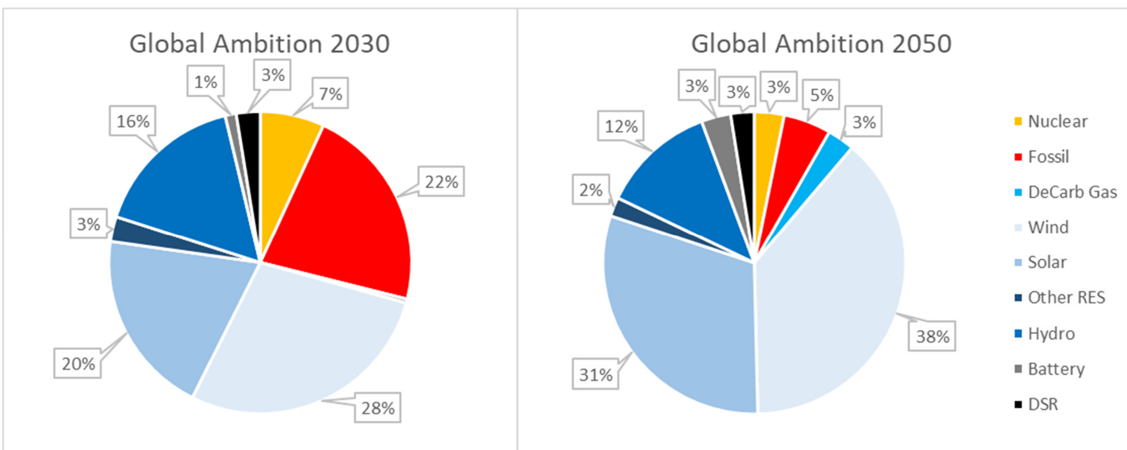


Figure 2-24 - Global Ambition scenario installed capacities shares at EU level: evolution from 2030 to 2050.

In Global Ambition scenario, total installed capacity increases from 1438 GW to 1960 GW in Europe. This corresponds to an increase of 36.2%. The share of non-renewable energy sources (nuclear and fossil) decrease from 29% in 2030 to 8% in 2050. The shares of wind and solar energy sources increase from 28% to 38% and 20% to 31% respectively. It is important to note, that the installed generation for P2G resources is not shown, because its share is less than 0.3% for all the target years.

The annual electricity consumption increases from 3592 TWh in 2030 to 3970 TWh in 2050. The largest increase in electricity consumption in percentage will be in Eastern Denmark (+58.6%), Latvia (+51.8%) and Lithuania (+37.3%), the largest increase in electricity consumption in absolute values will be in Spain (+72 TWh). The peak load increases from 584 GW in 2030 to 630 GW in 2050, the largest increase in peak load in percentage will be in Eastern Denmark (+54.2%), the largest increase in peak load in absolute values will be in Spain (+12.7 GW).

The changes of the share of different types of generation in Germany, Montenegro, Norway and Spain from 2030 to 2050 are presented in Figure 2-25, Figure 2-26, Figure 2-27 and Figure 2-28. The changes of the peak load, installed capacity and total demand in these countries in target years 2030-2040-2050 are presented in Figure 2-29, Figure 2-30, Figure 2-31 and Figure 2-32.

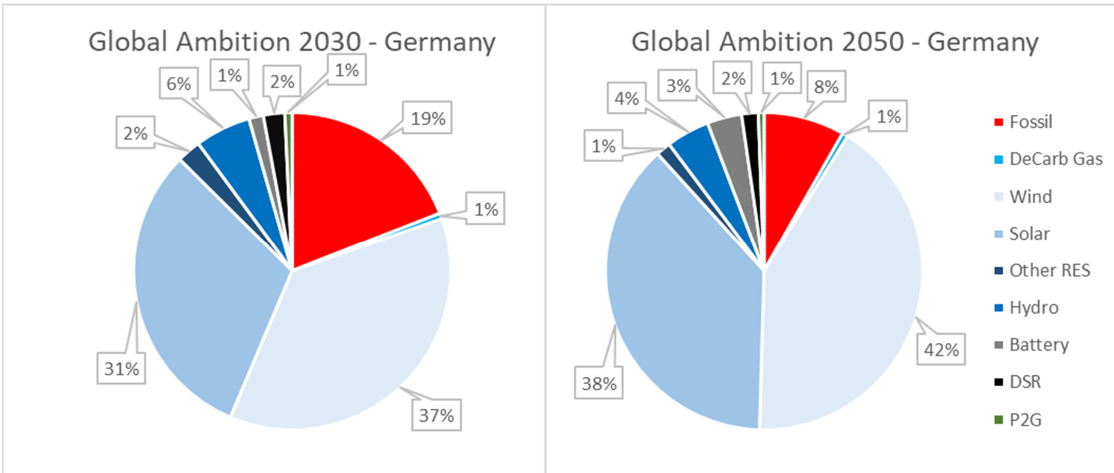


Figure 2-25 - The installed generation capacity in Global Ambition scenario in Germany in 2030 and 2050.

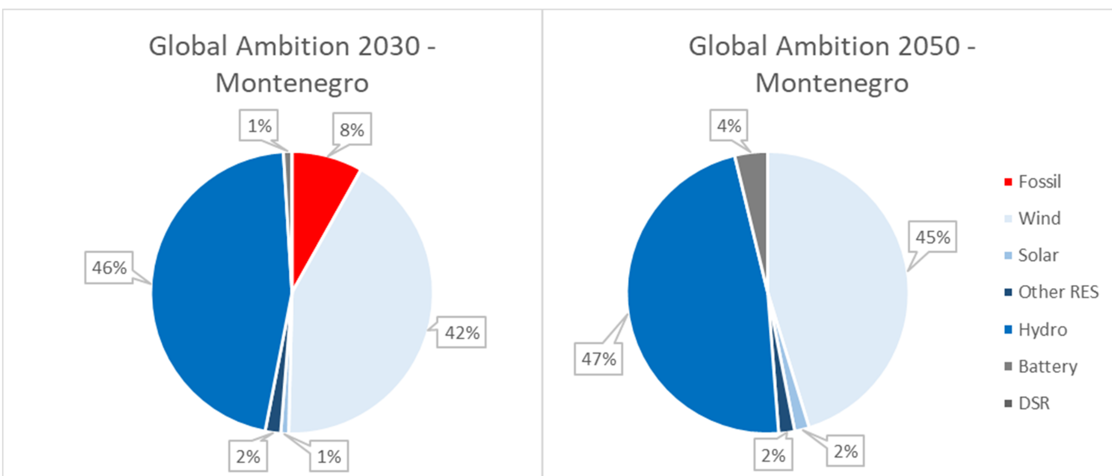


Figure 2-26 - The installed generation capacity in Global Ambition scenario in Montenegro in 2030 and 2050.

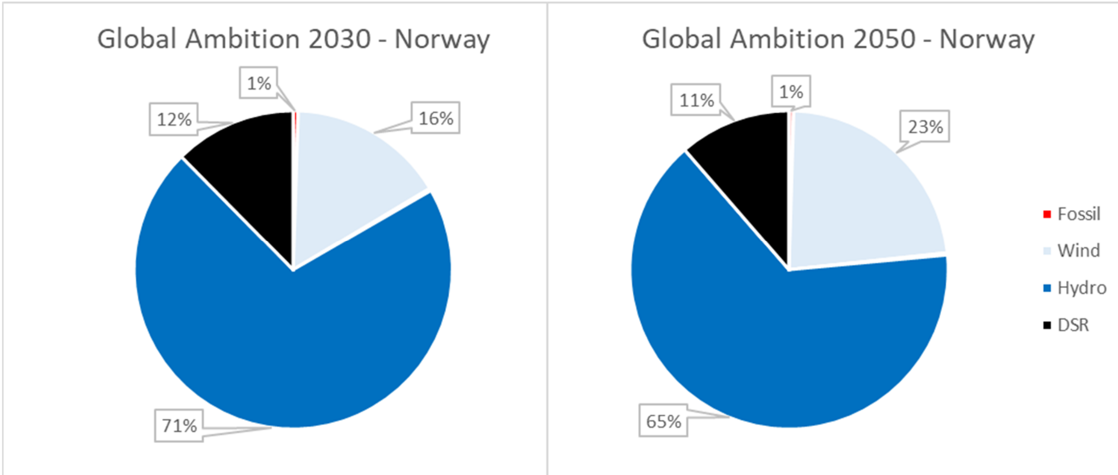


Figure 2-27 - The installed generation capacity in Global Ambition scenario in Norway in 2030 and 2050.

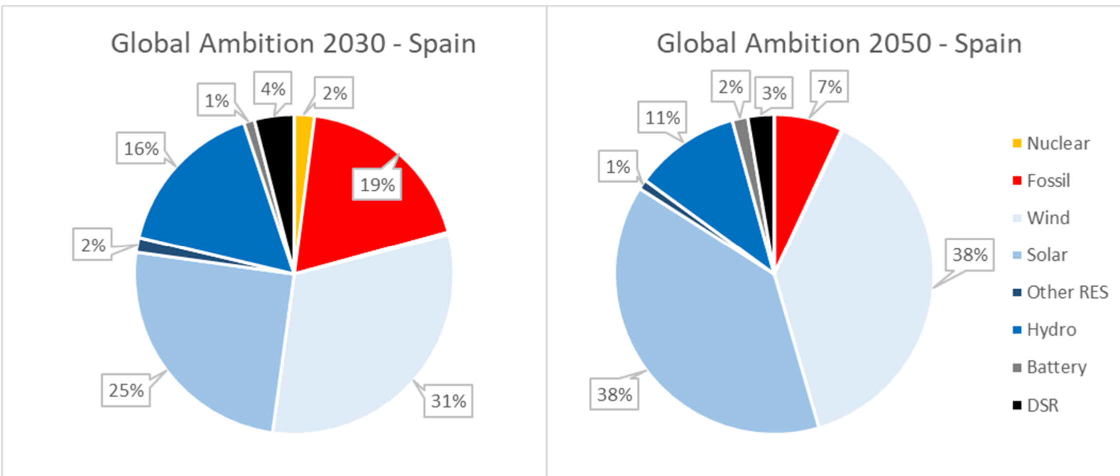


Figure 2-28 - The installed generation capacity in Global Ambition scenario in Spain in 2030 and 2050.

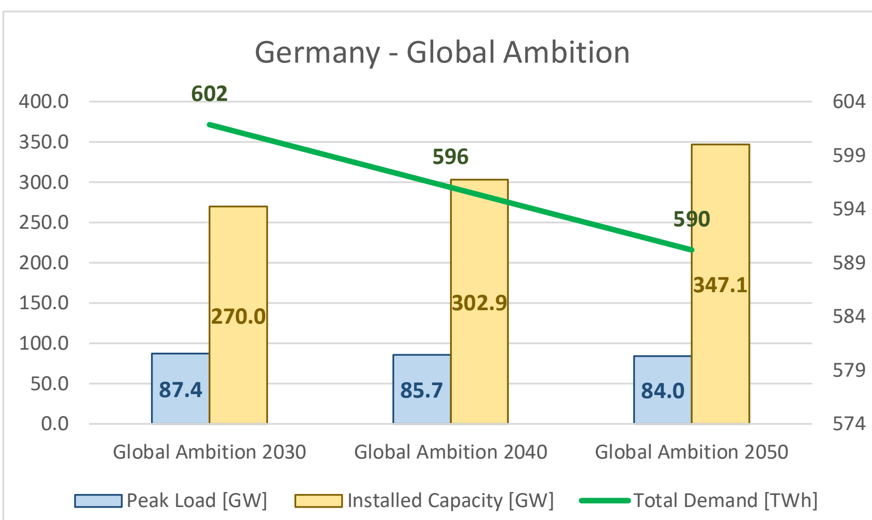


Figure 2-29 - The change of peak load, installed capacity and total demand in Germany in Global Ambition scenario.

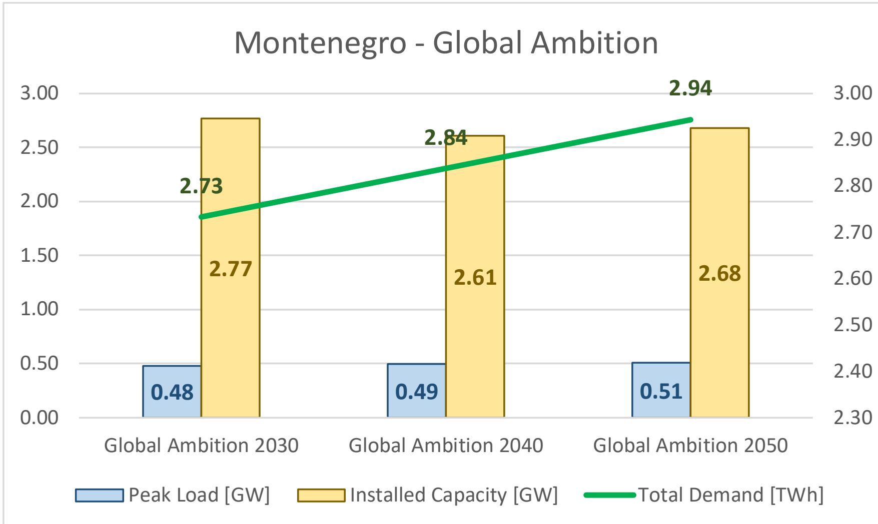


Figure 2-30 - The change of peak load, installed capacity and total demand in Montenegro in Global Ambition scenario.

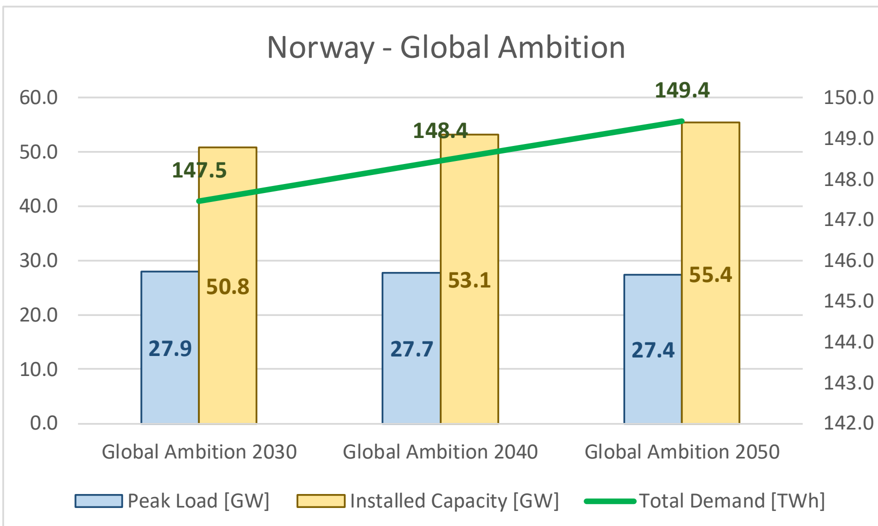


Figure 2-31 - The change of peak load, installed capacity and total demand in Norway in Global Ambition scenario.

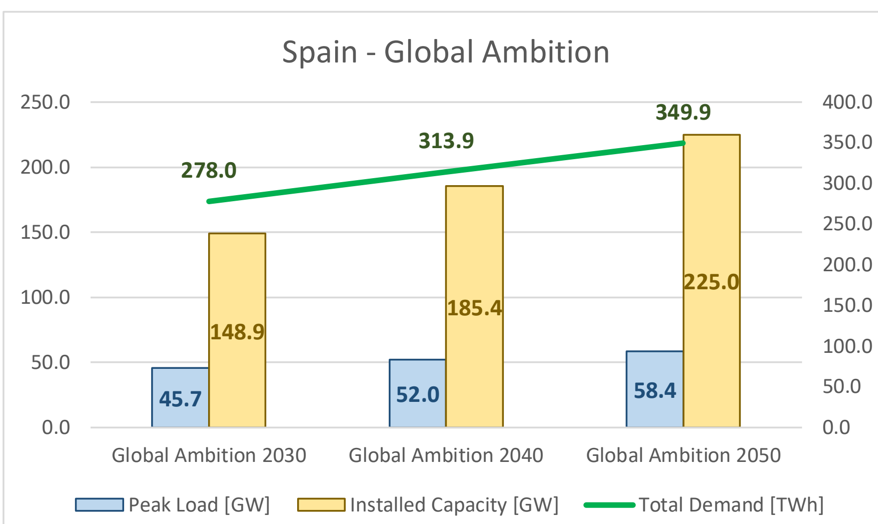


Figure 2-32 - The change of peak load, installed capacity and total demand in Spain in Global Ambition scenario.

From these figures it can be seen, that in Spain, taking into account the increase in installed generation capacity, the biggest increase is taken by solar generation (from 31% in 2030 to 38% in 2050), Montenegro will not have fossil fuel generation in 2050 with increase in solar (from 1% in 2030 to 2% in 2050) and battery (from 1% in 2030 to 4% in 2050) generation capacity, Norway will have mainly hydro generation (from 71% in 2030 to 65% in 2050, which reflects not the decrease of hydro generation capacity, but increase the share of wind), Spain will have the biggest increase in solar generation capacity (from 25% in 2030 to 38% in 2050). It is important to note that the total demand in Germany in Global Ambition scenario will decrease from 602 TWh in 2030 to 590 TWh in 2050.

The capacity reserves are remain the same in 2050, which are 3000 MW for Continental Europe zone, 1000 MW for Nordic countries zone and 1500 MW in United Kingdom and Ireland. The largest increase in FCR reserve will be in Spain (from 363.2 MW in 2030 to 492.1 MW in 2050), the largest increase in FRR reserve will be in Turkey (from 2651 MW in 2030 to 4592 MW in 2050).

2.6 Scenario Comparison

In order to have a clear vision of FlexPlan scenarios, a direct comparison between these is hereby presented. Figure 2-33 and Figure 2-34 depict, respectively, the total installed capacity per technology for

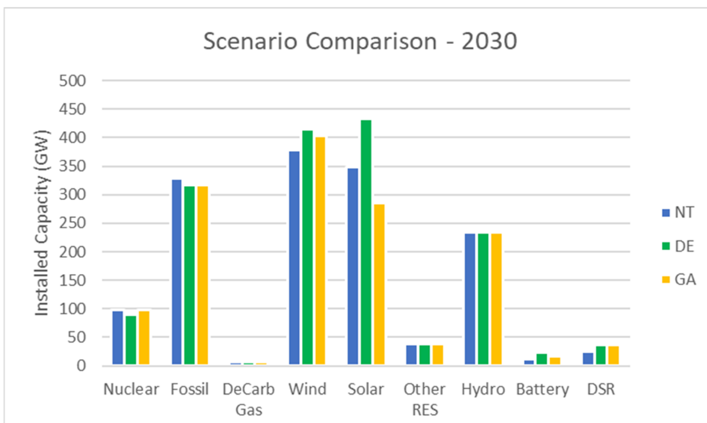


Figure 2-33 - Installed capacity in the three FlexPlan scenarios: 2030.

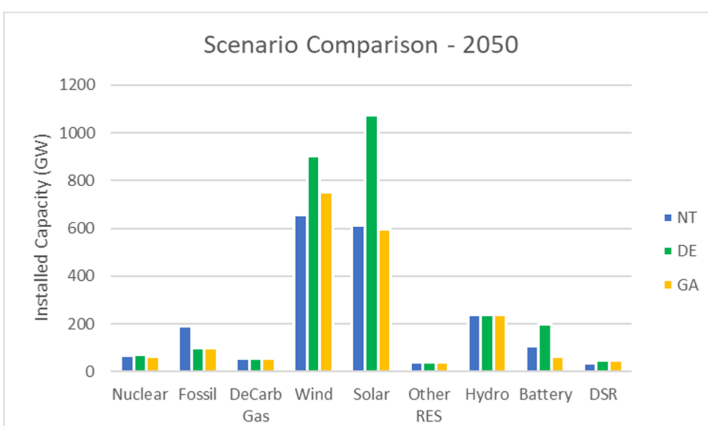


Figure 2-34 - Installed capacity in the three FlexPlan scenarios: 2050.

each scenario in 2030 and 2050.

Technology	Installed Capacity 2030 (GW)			Installed Capacity 2050 (GW)		
	NT	**DE**	**GA**	**NT**	**DE**	**GA**
Nuclear	98	90	99	66	69	62
Fossil	328	316	316	191	100	100
DeCarb gas	6	6	6	57	57	57
Wind	378	415	403	657	903	752
Solar	348	432	285	611	1076	596
Other RES	39	39	39	40	40	40
Hydro	234	234	234	239	239	239
Battery	12	23	17	109	198	62
DSR	25	37	37	34	49	49
P2G	3	3	3	5	5	2
TOTAL	**1472**	**1596**	**1439**	**2010**	**2737**	**1959**

Table 2-9 – Total installed capacities (rounded to GW unit) for all FlexPlan scenarios in 2030 and 2050.

Distributed Energy and Global Ambition scenarios represent more ambitious goals, as mentioned before. Thus, in order to achieve these goals it can be seen that these two scenarios consider a higher reduction of fossil fuels installed capacities, when compared to National Trends (316 to 100 GW compared to 328 to 191 GW). While in National Trends, fossil still accounts to 9.5% of installed capacity in 2050, this value is reduced to 3.6% and 5.1% in Distributed Energy and Global Ambition, respectively.

Regarding the total installed capacity, one can see that Distributed Energy scenario stands, when compared to the other two, as the total European installed capacity increases 71% from 2030 to 2050 (1596 GW to 2737 GW), while the other two scenarios have increases of 36 %. This is mainly due to the fact that in Distributed Energy, the decarbonisation is made through the usage of distributed energy resources (wind and solar), increasing substantially the total installed capacity needs to fulfil energy requirements. This increase is accompanied by a significant increase in storage devices (batteries), which aim to minimize the drawbacks of the volatility of solar and wind energy resources. It can also be seen that hydro is not expected to increase significantly from 2030 to 2050, and the increase of the share of RES and decarbonisation is always achieved (although following different strategies) using other renewables.

3 Grid Data

The analyses for the six regional cases and the consequent validation of the FlexPlan tool requires the existence of a complete electrical grid model which includes the grid topology, parameters of grid elements and location of load and generation centres (together with typical parameters for generation units). In order to provide coherence to the project results, the used grid model should have similar characteristics (similar level of detail) for the different regional cases, taking into consideration the possible restrictions in data collection for this purpose. However, the different regional cases might have different data access restrictions, resulting in small differences among the level of detail for the different regions.

As the FlexPlan tool aims at contributing to long term planning studies, the used grid model must be easily adaptable and flexible to accommodate new planned solutions (results of FlexPlan tool). Additionally, one of the goals of FlexPlan is to perform a joint planning for Transmission and Distribution systems. Thus, the used grid model needs to include both grids at regional case level. Taking into consideration that the European grid is fully interconnected and that it is also the aim of FlexPlan to perform a study at pan-EU level, the following approach was considered for the creation of a FlexPlan grid model:

- Utilization of a realistic Pan-EU transmission system model, from which individual regional case grid models can be extracted (leaving coherent equivalents to the remaining network);
- Addition of distribution grid models to the different RC transmission networks.

The next sections describe the followed approach to gather the required data to create the different regional case grid models, both at transmission and distribution levels.

3.1 Pan-EU Grid Model

The existence of a complete transmission system model for each one of the regional cases is of upmost importance to validate the FlexPlan tool, through its combination with the aforementioned scenarios data. In order to have a coherent approach among the different regional cases, the goal is to use a grid model with similar levels of detail for the different countries considered. This goal can only be reached if a pan-EU grid model is used as the base grid model, and then separated into the different regional case networks, which share borders among them. In order to achieve this goal, the FlexPlan team decided to search for existing Pan-EU Transmission systems models that could be used as main datasets. Since scenarios data presented in section 2 is mostly collected from TYNDP studies from ENTSO-E, then this entity should also be considered as a main source of data for the Pan-EU transmission system model. ENTSO-E uses a Pan-EU Transmission Grid Model for the preparation of the TYNDP studies [11]. The last version of this dataset, used in TYNDP 2018, is available through the signature of a Non-Disclosure Agreement (NDA) with ENTSO-E. In order to share the dataset among the FlexPlan consortium without raising any issue related to the confidentiality and non-disclosure clauses of the NDA, each member of the consortium involved in the regional cases execution requested separately the dataset from ENTSO-E and each request was positively accepted. This grid model was then used as the main source of data for the grid models to be considered in FlexPlan.

The received ENTSO-E grid model dataset is composed of 25 sets of files in Common Grid Model Exchange Specification (CGMES) format, one for each country in continental Europe and an additional CGMES file establishing the border conditions between the respective countries. The grid model correspond to a 2025 operational scenario with generation and demand corresponding to market simulations performed by ENTSO-E in TYNDP 2018. The model contains network data for voltage levels between 110 kV and 750 kV. All elements connected to 220 kV and above levels are modelled explicitly while branches and substations below this threshold might not be represented in detail, depending on the country analysed. Load values are represented aggregated in the Extra High Voltage (EHV) connection point and embedded generation is connected to the near EHV or High Voltage (HV) node.

As already described in previous paragraph, the model is made available by ENTSO-E in CGMES format, which has a well-established set of syntax rules but has some limitations to perform power system studies, as specific software is required to work with this format. Hence, in order to have a more user-friendly format, which the different regional case leaders (and the FlexPlan tool) can use, a process was created to convert the model and separate it into the different regional case networks. This separation into individual regional case networks is important as the whole continental Europe model provided contains a high number of elements that would create a simulation burden without any advantages as each regional case looks into the internal grids, together with well-established border conditions through the interconnections with other countries and not the overall European system.

Although this conversion and the validation activities are performed in the scope of WP5 of FlexPlan, it is considered that a summary explanation of the conversion model should be given in this document, as a common set of rules is used by the different regional cases, to ensure that the border conditions are satisfied. This data conversion process is depicted in Figure 3-1.

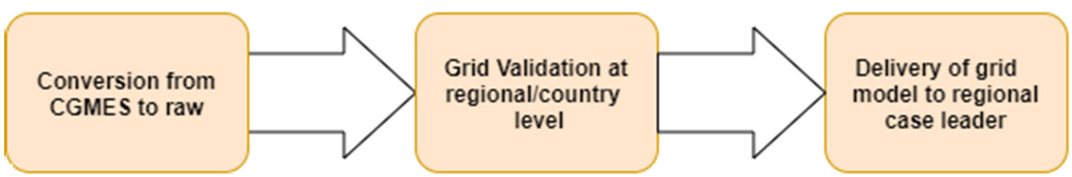


Figure 3-1 - ENTSO-E grid model processing approach.

The model is firstly converted into a well-known and commonly used format by TSOs (.raw format used in SIEMENS PTI PSS/E). The conversion is made at regional case level. As an example, for the Iberian regional case, the Portuguese and Spanish transmission systems should be converted together, using the boundary file to establish the borders with the remaining countries. In cases where this conversion is performed successfully, the regional grid model is then considered accepted and it shall be complemented with additional data sources to be used in the scope of the regional case activities. In the case where the conversion generates any issue (e.g. resulting in non-convergences in steady state conditions), the countries are converted individually to narrow down the possible source of the problem. After the grid conversion and validation (using a power flow analysis), the regional case transmission system model is then given to the regional case leader for further adaptations.

3.2 Additional Transmission grids data models

Although the team decided to use the grid dataset from ENTSO-E as the main transmission system model, a first analysis on the received data allowed identifying different gaps that would need to be solved with additional data sources to ensure that the regional cases have all necessary data for implementation of the FlexPlan tool. This is a core point to allow for a full demonstration of the envisioned capabilities of the FlexPlan tool. Four main issues were identified in this dataset:

- Absence of grid model for Nordic countries (Norway, Sweden and Finland), which are required for the Nordic regional case;
- Absence of grid models at 150/110 kV voltage levels in different countries, together with absence of sub-transmission levels.
- Absence of geographic information data for grid nodes, which is a required input in the FlexPlan Tool (all nodes including generation units) and also for MILES tool;
- Incomplete definition of type of generator units (thermal, wind, solar, etc), which is also a required input for the FlexPlan Tool and for MILES tool.

These three gaps resulted in the need to look for additional open source data sources in order to have regional cases grids that contain all the information required to demonstrate the capabilities of the FlexPlan tool, which include, as an example, the impact on the air quality or carbon footprint of electricity generation units.

3.2.1 Other grid data sources used

In addition to the ENTSO-E grid model, the team identified different open-source pan-European grid models. These can be used as an alternative where data gaps are identified, as in the aforementioned case of the Nordic regional case, but also to complement the ENTSO-E model. One possible usage example for these datasets is in the clarification of some of the characteristics existing in the ENTSO-E dataset. The grid models provided in the ENTSO-E dataset are anonymized by each one of the correspondent TSOs, thus providing a possible heterogeneous grid model for different countries, even inside the same FlexPlan regional case. Thus, these open-source models can be used to allow a quicker identification of the grid topology from the ENTSO-E model.

The team identified two possible alternatives for open source models of pan-European grids:

- PyPSA-Eur [12]- European power system model for transmission networks, covering all ENTSO-E area. AC lines at 220 kV and higher voltages are fully modelled and all DC lines and substations are also identified. Conventional power plants are based on an open database and the dataset also contains time series for demand and variable renewable generation, including geographic potentials for the expansion of wind and solar power. The model contains 8011 buses and 9856 transmission lines;
- PanTaGruEl [13] - contains a dynamical grid model designed to investigate the propagation of disturbances in the continental European transmission grid. Similarly to PyPSA-Eur, it also uses data extracted from ENTSO-E interactive map and it allows dynamic simulations as well. The model contains 3809 connected buses and 4944 transmission lines at the 220 kV voltage level and above.

From a first analysis of the two open-source models, it seems that PyPSA-Eur contains a more detailed model, including also the Nordic countries, while PanTaGruEl only has data for continental Europe. PanTaGruEl has the advantage of also allowing to perform dynamic simulations, but this is out of scope of the FlexPlan project. Hence, the PyPSA-Eur model is selected to complement, whenever necessary, the ENTSO-E grid dataset.

In PyPSA-Eur, the aggregation of the information is obtained by processing publicly available and open databases from different sources. The transmission grid data is obtained by an automatic processing of ENTSO-E interactive map, using the following set of rules:

- Voltage levels and bus coordinates are directly extracted from the interactive map;
- Line parameters (x and r) are assumed as constant for the three voltage levels (400/380, 300 and 220 kV);
- HVDC lines are included;
- Transformers have been assumed with a standard size of 2 GW (equivalent to 4 tranformers of 500 MW each), with a reactance of 0.1 pu.

The buses are defined in terms of node name, eventual power plant type and capacity, x and y coordinates, voltage level, and miscellaneous information. The power plant database is built by merging information from different sources (OPSD, ENTSO-E PPL, GEO, CARMA, DOE ESE, GPD). Wind, solar and hydro-electric time series availability are extracted from historical weather data (such as CORINE Land Cover database, SARAH-2 and ERA5), which defines the potential generation from renewable energy source per unit of inland and offshore surface. Electrical load demand time series is obtained from ENTSO-E website (at country level aggregation). The demand time series is distributed to the country substations according to regional GDP and population, in percentage 60% and 40%, respectively.

The whole dataset is built in the format *.nc, to be processed with the pyPSA software [10], which is a Python based open-source software for load flow calculation and investment optimization. Nonetheless, in FlexPlan, only the grid model is extracted from PyPSA-Eur, whenever necessary. Other quantities such as renewable energy and load time series are obtained from MILES software, as the next step of the project as already indicated in section 1.

3.2.2 Nordic Regional Case

The PyPSA-Eur database has been analysed for the Nordic Region, including Norway (NO), Sweden (SE), Finland (FI) and Denmark (DK). The number of buses of the whole region is reported in Table 3-1, classified for country and voltage level.

Voltage level (kV)	NO	SE	FI	DK
380	42	83	43	32
300	100			
220	2	110	26	11
(BLANK)		1		2
TOT	144	194	69	45

Table 3-1 - Number of buses from pyPSA-EUR database for country and voltage level.

The buses have been further analysed and classified for type of power plant connected to each bus. The results of the analysis is reported in Table 3-2. The generation assets in the dataset are connected to buses allocated to specific countries. Based on this coupling the installed generation capacity per country is assessed. As hydropower is important in the Nordic area, also storage assets with their generation capacity are assessed. This leads to an overview of generation resources for selected areas of the power system.

Type	NO	SE	FI	DK
Brown coal / lignite			2	
Converter Station		5		1
Fossil gas	1			1
Fossil oil			1	1
Hard coal				2
Hydro mixed pump storage	4			
Hydro pure pump storage	2			
Hydro pure storage	56			
Hydro run of river & pondage		65	7	
joint	6	24	2	8
Mixed fuels				2
Nuclear		3	2	
Other or not listed		3		
Substation	73	85	55	27
Substations + power plant	2	2		
Wind farm		7		3
TOT	144	194	69	45

Table 3-2 - Classification of buses for type of power plant connected.

Assessing the installed capacity in the Nordic area the following overview is defined, see Table 3-3. It can be observed that the capacity for wind and solar power is zero. This is as electricity generation is defined based on times series of generation. Furthermore, the sum of generation capacity indicates that there is capacity missing. This accounts specifically for Denmark and Sweden.

Type	NO	SE	FI	DK
Coal	-	130	3040	3630
Gas	1225	708	1325	1530
Oil	-	2135	1225	665
Hydro	33181	13806	2570	-
Nuclear	-	9532	2784	-
Biomass	56	725	3585	195
Solar	-	-	-	-
Wind	-	-	-	-
Sum	34462	27036	14529	6020

Table 3-3 - Installed generation capacity in the Nordic area for defined generators in MW.

The Nordic system with its renewable sources has some different characteristics than the continental European power system. As electricity generation is located were the resources are, transmission infrastructure and capacity are of great importance. Assessing the location of the hydropower resources in the dataset shows that hydro capacity is concentrated in about 15 nodes throughout the Nordic system, which might lead to the underestimation of restrictions in the transmission system.

In order to improve the dataset, there are some available sources for Norway [14], but much more limited for Sweden and Finland. This additional information will be used for the regional case studies to update and improve the dataset, but it might not be essential for the pan-European analysis. This is the case as the description at country level is representative.

3.3 Distribution grids data

The regional cases also need to consider distribution grids as one of the goals of FlexPlan is to perform integrated transmission and distribution planning. In contrast to transmission systems, there is not a unified dataset for distribution models and the amount of public available data is even lower. Additionally, it is impossible to fully model distribution systems, as these have a much higher number of nodes than transmission systems.

With the goal to validate the FlexPlan tool using also distribution systems, the team will model distribution systems, which will be incorporated into the currently existing transmission grid models. The modelled distribution grids will be representative parts of the existing distribution grids in the different regional cases and will include different characteristics. These can include, as example the modelling of different distribution grids representative of high density and low density (urban and rural) networks. For this purpose, the modelling tool described below and based on real statistics received from DSOs will be applied, creating synthetic distribution networks.

Even considering synthetic networks, the representation of full distribution models, from HV to Low Voltage (LV) is not feasible neither advisable in a project such as FlexPlan, which deals with power systems at pan-European level. Thus, the modelled distribution systems will only consider the Medium Voltage (MV) level, which is normally operated with by means of radial grid structures and managed by distribution system operators. This selection ensures that all the regional cases will be modelled with the same degree of detail, even when DSOs manage also higher voltages. Distributed generation, which has not affected distribution network planning during the past decades, is also included in the processed synthetic distribution systems, having considered that their current structure is only marginally affected by it.

3.3.1 Analysis of real distribution networks

The first step related to the development of the synthetic network generator has dealt with the analysis of the models of real MV systems, which have been collected from public sources [15], but also acquired directly from Italian network operators during recent research projects. According to the analysis carried out on the available networks, an initial clustering has been performed: about 100 feeders (15 primary substations) have been classified as urban, while other 25 feeders have been categorized as sections of rural networks. The urban set is more homogeneous (in fact, it refers to the same geographical area), while the rural networks present a higher level of variability. However, the available data cannot be intended to be representative of the whole Italian scenario, even if it covers different geographical areas and operators. During the progress of the project, the methodology and the statistics will be extended as soon as additional networks will be collected/generated from other sources.

The design of the tool is based on the evaluation of three main characteristics: the topology, the electrical properties of lines, and the load distribution. For the last parameter, the contractual power of customers has been considered representative of the actual consumption. Concerning the generation units, their distribution is not considered since, historically, networks are used to be planned on the basis of the expected energy demand; in fact, the analysis of the parameters related to existing networks demonstrates a poor correlation with the data referred to distributed generation.

1. Topology

The topology represents the graph structure of a network (Figure 3-2) and many properties of the grid come from it [16]. The number of nodes and ramifications have been studied in detail for each level of the tree (Figure 3-2), in accordance with the statistical studies of graph theory[17].

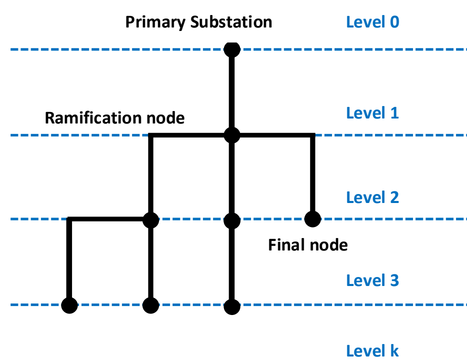


Figure 3-2 - Topological representation of a distribution network (level: number of nodes from the substation).

The percentage of busses referring to a given level is a basic property of a network (Figure 3-3) and its analysis demonstrates that the two groups of networks (rural/urban) have similar distributions. In both cases, the number of nodes increases rapidly in the first 10 levels and then decreases exponentially by following the empirical expression:

$$N_k = N_m C^{k-m}$$

where N_k is the number of busses at level k, m is the level where the number of busses is maximum and C is the exponential base (which is determined on the basis of the observed networks). The similar shape of the two curves can be explained by the general planning rules. With the hypothesis of a uniformly distributed load, the number of nodes of the network should increase linearly in order to maintain the same spatial density. Once a certain distance is reached, the network starts to overlap with other primary substations areas (this allows reconfiguration in case of line failures). At this level, the number of nodes normally decreases. Also the experience demonstrates that rural and urban areas are designed with similar criteria and, the main difference is represented by their geographical extension that can be easily modelled with a scaling factor. According to this, the lengths of the lines may vary significantly, due to the different load density, but the topological properties remain similar (Figure 3-3).

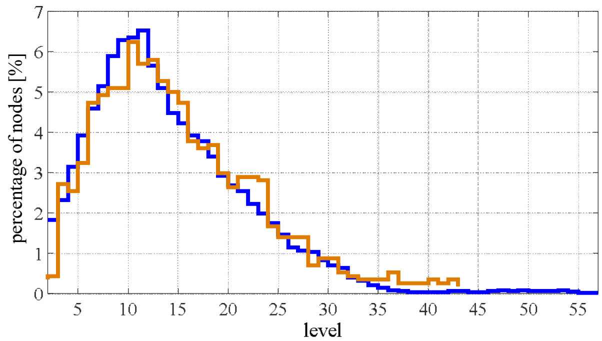


Figure 3-3 - Distribution of the busses in function of the topology level, for the rural (orange) and urban (blue) networks.

For the real networks considered by this investigation, it has been noticed that each bus has a maximum number of ramifications (the probability of having 0, 1, 2 and 3 ramifications is expressed with $P_{0,1,2,3}$ and reported in Table 3-4 and Table 3-5). For these parameters, it is possible to clearly distinguish urban from rural networks. The first ones are characterized by feeders with many ramifications (high value of P_1), while the second ones have definitively higher values of P_2 and P_3. Finally, the mean number of ramifications computed by:

$$r = \sum_{i=0}^{3} i \cdot P_i$$

is quite similar among the two groups: 0.86 for urban and 0.91 for rural, which demonstrates the topology similarities between the two clusters.

Type of busses	Type of network	
	Urban	Rural
P_0	17%	40%
P_1	80%	30%
P_2	3%	28.8%
P_3	0%	1.2%

Table 3-4 - Percentage of the different busses with 0, 1, 2 or 3 ramification for the two groups between levels 10 and 30.

The topological differences can be better described by looking at Figure 3-4. As mentioned above, urban networks should cover a more uniform and dense load distribution, thus straight lines with few derivations represent the most efficient solution. Instead, in case of rural areas, more derivations and longer lines are needed to supply a less dense and more sparse loads.

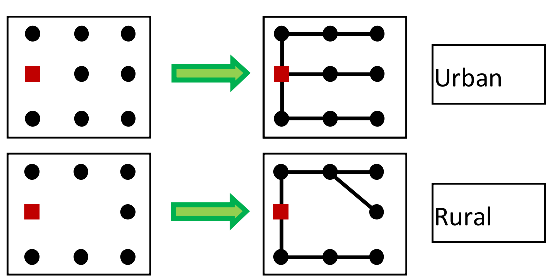


Figure 3-4 - Schematic representation of topological differences between urban and rural networks.

2. Electric parameters

The most important electrical properties of a network line are represented by its resistance R, reactance X, and susceptance B. Normally, in distribution networks, the value of R is the most relevant parameter, since it is more connected to the physical characteristics of the lines (e.g. section, material, length, etc.). The cumulative distribution function of the total resistive distance from the primary substation is particularly interesting (Figure 3-5): the resistivity of rural networks is much greater than the one featured by urban systems, having a mean line resistance of 0.4 Ω and 0.1 Ω respectively. In addition, the analysis shows that the resistance is rather uniform over the levels: this can be seen by the almost linear slopes of the two curves in the central part of the graph. Two very similar distributions are found by normalizing the obtained curves to their respective mean value (Figure 3-6). This behaviour is connected to the similar distribution of nodes (Figure 3-3) and the uniformity of R (Figure 3-5).

Finally, another important parameter is the R/X ratio of the branches, which is about 1.5 for the urban and 2.5 for the rural networks. The discrepancy among ratios can be explained with the different lines typologies normally adopted for the two systems: cables for urban and overhead for rural networks.

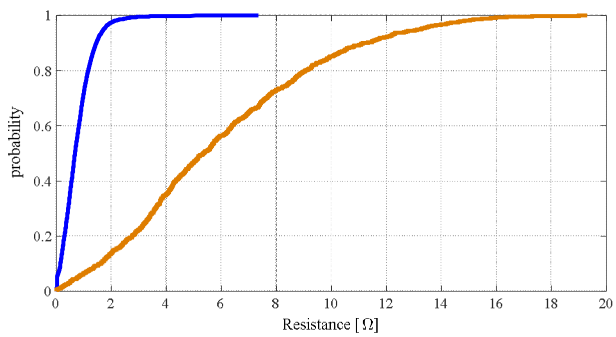


Figure 3-5 - Cumulative distribution of the electric distance of busses from the primary substation for the rural (orange) and urban (blue) networks. The slope of the curves is proportional to the resistance.

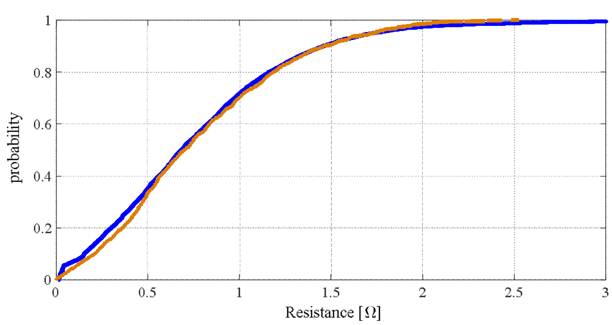


Figure 3-6 - Cumulative distribution of the electric distance of busses from the primary substation for the rural (orange) and urban (blue) networks, normalized to the average resistance value.

3. Load distribution

The distribution of the nominal load is the last considered parameter (Figure 3-7). Urban networks are characterized by a high total load if compared with the one of rural networks. This can be explained with the higher customer density typical of urban areas. However, load seems to be uniformly distributed over the topology levels for both the considered network clusters. This is in agreement with the hypothesis that in the planning phase the network is designed to cover the load uniformly.

Another important difference is represented by the number of loads connected to different bus typologies (Figure 3-8). For urban networks, the load connections results to be quite not dependent on the bus typology: this happens because the load is concentrated around the primary substation and the lines cover it more uniformly (Figure 3-4). On the contrary, rural networks are used to have loads connected to the final busses of the tree (the ones with no ramifications). Surprisingly, urban networks seem to have a limited amount of loads connected to the final busses: this can be explained by noticing that these sections are aimed at hosting the operation switches which are activated in case of lines failures and reconfiguration actions with neighbouring networks.

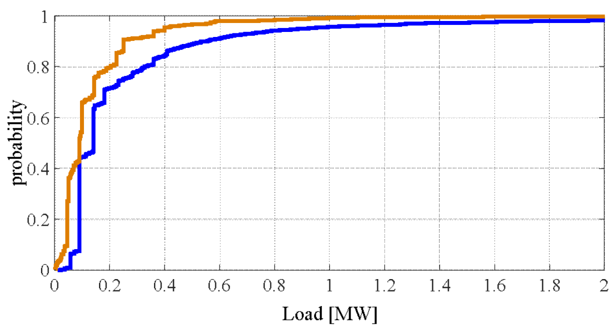


Figure 3-7 - Cumulative distribution of loads for the rural (orange) and urban (blue) networks.

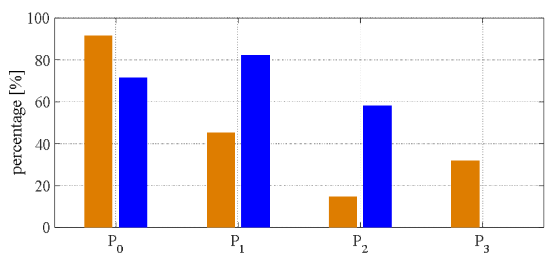


Figure 3-8 - Percentage of busses connected to loads in function of the type of busses for the rural (orange) and urban (blue) networks.

3.3.2 Parameters for the synthesis of distribution networks

Thanks to the analysis reported above, some network characteristic parameters have been identified. In many cases not all the information reported in the previous sub-sections are necessary to describe an electric distribution system. In fact, the analysis demonstrates that many parameters are almost uniform over the levels: for example, impedance and loads can be reasonably considered equal for all the branches and nodes. In those cases, their average value can be used.

As anticipated above, also the relationship between parameters have been investigated (e.g. impedance of a branch with respect the distance from the primary substation), but small correlations have been identified. More significant relationships were found between the value of parameters and the network type. In particular, the average number of nodes with 0, 1, 2 or 3 ramifications $P_{0,1,2,3}$ follows a semi empirical relationship:

$$\begin{cases} P_0 = 0.38 - 0.23x \\ P_1 = 0.30 - 0.50x \\ P_2 = 0.30 - 0.25x \\ P_3 = 0.02 - 0.02x \end{cases}$$

where x is a parameter related to the urban/rural nature of a network ($x = 0$ and $x = 1$ for rural and urban areas respectively). This relationship is in good accordance with the tested networks as reported in Table 3-5. As anticipated above, this synthesis parameter, together with other relevant variables (e.g. mean impedance), can be used to classify networks in different clusters.

Also for the electric parameters some consideration can be made (Table 3-6). Excluding the CIGRE network, a uniform trend can be observed on the variation of R and X. The values of these parameters seem to be correlated to the total number of levels, the total distance and the load distribution, however a larger sample of networks is needed for further considerations. The experience and the feedback provided by DSOs during the progress of the project will be crucial for the identification of the selected network parameters and correlations.

Percentage of ramification	Rural	Network test 2	CIGRE	Network test 1	Urban
P_0	36%	28%	27%	21%	13%
P_1	33%	47%	55%	60%	81%
P_2	29%	23%	18%	18%	5%
P_3	2%	1%	0%	1%	≈0%
x	0%	34%	50%	60%	100%

Table 3-5 - Percentage of the different types of busses within the analyzed networks set and value of the fitting parameter x.

Average branches parameters	Rural	Network test 2	CIGRE	Network test 1	Urban
R [Ω]	0.394	0.162	0.718	0.131	0.076
X [Ω]	0.204	0.105	1.026	0.082	0.079
$(R)/(X)$	1.93	1.55	0.7	1.60	0.96
(R/X)	2.46	1.89	0.7	1.71	1.49

Table 3-6 - Average values of the electric parameters of network branches.

Many other parameters and their correlation factors have been considered. Among them, the analysis of the line loading limit is particularly interesting. Even though no particular correlations with other properties were found (e.g. between primary and secondary lines), some general behaviours of the current limits can be observed (Figure 3-9).

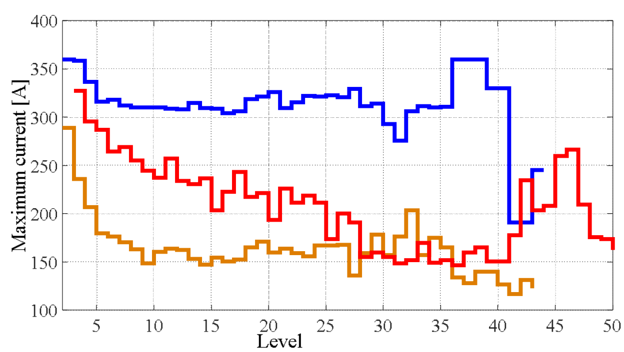


Figure 3-9 - Mean value of maximum current limits in function of the level, for the rural (orange) and urban (blue) networks and test network 2 (red).

First of all, the average loading limit of urban networks is larger with respect to the rural systems ones. In addition, urban networks feature the largest loading capacities both at the beginning and at the end of the feeders: this happens because the planning of these kind of networks takes into account the possibility of connecting the entire system to a neighbouring primary substation in case of failure of the current configuration. The maximum current limits of rural networks feature an almost monotonic decreasing shape. A small increase near the end of the feeder can be still observed but it is less evident, since the reconfiguration possibilities are more limited. The test networks, instead, have an intermediate behaviour, and preserve the local peak at the end of the feeder.

3.3.3 Generation of synthetic distribution networks

Starting from the synthesis parameters described within the previous sub-sections, a method to generate random synthetic networks has been developed. The network generation consists in a three steps methodology:

1) A network topology is randomly generated (Figure 3-10);
2) Values of impedances are randomly assigned to branches respecting the desired distribution;
3) Loads are connected to the busses respecting the given distribution.

The values of the parameters are assigned with a stochastic procedure: they are taken randomly, following the probability density functions which results from the analysis described above. As anticipated, impedances and loads can be reasonably assumed to have equal values, since the analysis reported in the previous section shows that they are rather constant.

Thanks to the low correlations between the investigated parameters, the three proposed steps are in general independent. Of course, possible correlations among the parameters can be taken into account (dependency between resistance value and network typology). Finally, in order to consider the ramification of the network tree (represented by the probabilities $P_{0,1,2,3}$) two sets of values can be generated: one for the network section in which the amount of busses per level is increasing, and the second one for the most remote network areas (in which the amount of buses is decreasing exponentially).

The stochastic procedures adopted in all the three steps always return different grid topologies (Figure 3-11), with very specific behaviour but with common characteristics. It is also found that, the stochasticity of the first step (topology) greatly impacts the network generation process and it must be carefully calibrated, as shown in the continuation of this Chapter.

The proposed method is applied to generate networks by taking as input the values extracted from the previously described rural and urban networks. The random generation process preserves the general topology characteristics, and this can be seen in Figure 3-12, where the obtained distribution is overlapping the reference ones.

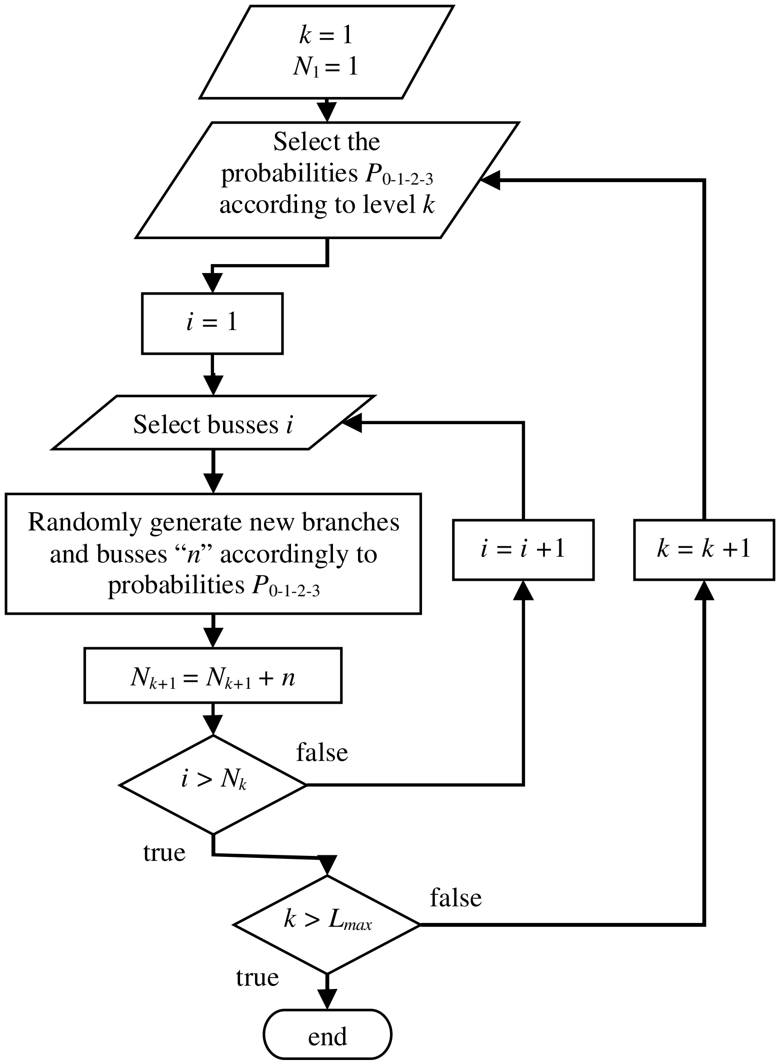


Figure 3-10 - Procedure for the generation of the topology. L_{max} is the maximum number of levels, k is the level generated, N_k the number of busses of k-th level and i is the busses. The procedure can be extended by adding, for example, a minimum number of levels.

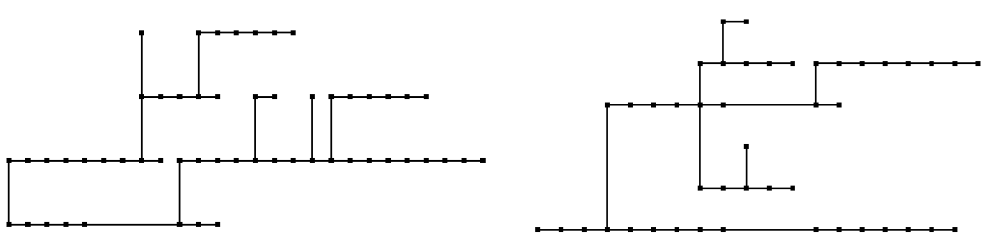


Figure 3-11 - Examples of two generated feeders.

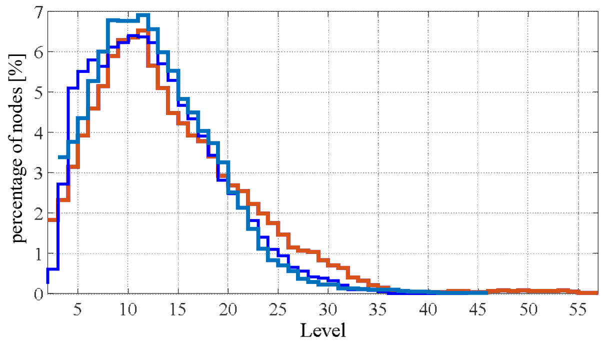


Figure 3-12 - Distribution of the busses in function of the level for the urban (blue), the synthetic urban (light-blue) and synthetic rural (red) networks.

Other parameters (e.g. average resistance, load, etc.) are inherently conserved during the processing of the artificial network. The two distributions of resistance values are approximately similar (Figure 3-13) except for the rural networks since few lines are featuring very different resistivity on the feeder backbone. The stair shape is due to the use, in each level, of same resistance value.

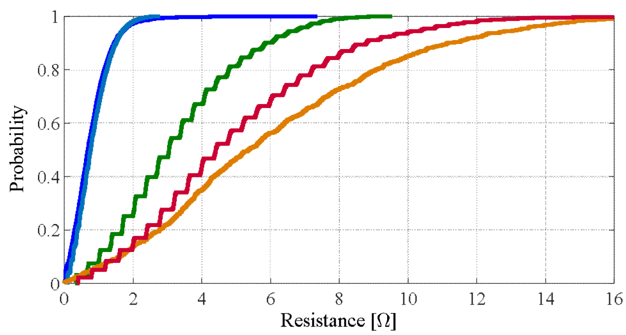


Figure 3-13 - Cumulative distribution of the electric distance of busses from the primary substation for the rural (orange) and synthetic rural (red) network, urban (blue) and synthetic urban (light blue) network and intermediate network (green).

In order to validate the method, it is important to study the combination of different parameters. One is the distribution of load as a function of the electrical distance from the primary substation (Figure 3-14). The shape of the curves obtained for the synthetic networks are similar to the ones extracted from the real ones. The discrepancies highlighted in Figure 3-13 for rural networks are not evident thanks to the averaging effect of considering both load and resistance. Even better agreement can be found if more realistic distributions of resistance and loads are generated.

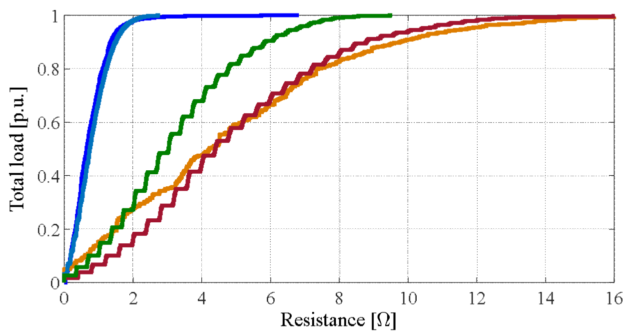


Figure 3-14 - Cumulative density function of the load in function of the electrical distance for a set of real urban (blue) and synthetic urban (light-blue) networks, real rural (orange) and synthetic rural (red) networks, and an intermediate synthetic network (green).

The results clearly demonstrate that the calculated parameters are matching the ones extracted from the reference networks. This means that the proposed method is consistent and does not introduce relevant distortions in the synthetized characteristics. Finally, the approach allows the generation of networks with other properties, which can be obtained by playing with the parameter x (see section 3.3.2), the resistance, load and generation units. More specifically, distributed generation will be randomly allocated within the synthetic networks, having assumed that it is mostly based on the availability of the primary source (especially for renewables) and does not depend on the previous configuration of the grid.

4 Additional Data needs

In addition to the different scenarios considered for the three target years and a grid model, the demonstration of the FlexPlan tool through the regional cases has additional data needs. These are identified and categorized into the following subsets:

- Geographic information;
- Generation data;
- Landscape;
- Air quality;
- Carbon footprint.

Taking into consideration these data needs, the team researched the best approach to obtain these data, either using already identified data sources or resorting to additional sources. The next sections shortly describe why these data needs were identified and the existing data sources that can be used for collection of these data, ensuring the full applicability of the FlexPlan tool developed solutions.

4.1 Geographic information

The FlexPlan tool is designed for grid planning studies, evaluating grid expansion candidates including multiple technologies. In order to perform a sound analysis, the geographic location of the grid nodes is a required information. If this information is not considered, the solutions provided by the tool might result in an unreasonable cost or even in an unfeasible solution. Thus, the existence of geographic information for the grid nodes is necessary, to ensure a correct usage of the FlexPlan tool. Additionally, the first step in the consideration of the regional cases correspond to the creation of scenarios to be simulated by MILES. The regionalisation module of MILES will use the National level data obtained from the scenarios described in section 2 and divide that data into clusters which correspond to a zonal cluster or, in the limit, to a node in the network model. MILES needs as inputs a full set of these clusters. Thus, if the geographic information of the grid nodes is provided as an input for MILES, the regionalization process will already provide results at a nodal level, thus reducing the need for additional effort on performing this activity.

As already mentioned, the main grid dataset chosen to be used in FlexPlan is the official pan-EU transmission network model from ENTSO-E. However, this model does not include any information regarding geographic location of grid nodes. As an alternative solution, and since this dataset is already available, the team decided to create a methodology to be applied at regional case level, using the ENTSO-E grid dataset as main grid model, complemented with data from PyPSA-Eur model for identification of nodes and geographic location information. This methodology depicted in Figure 4-1.

The methodology described is applicable to internal grid nodes and also to generation nodes, since the geographic information of generators is also an important information to have available at regional case level. The generation data, including geographic location information, is described in section 4.2. This strategy is applied for the different regional cases in FlexPlan. Each case will have its own challenges as the existing data from the ENTSO-E grid model has different particularities for the different countries considered. In some countries it's straightforward to identify the grid nodes, while in others this represents a higher challenge.

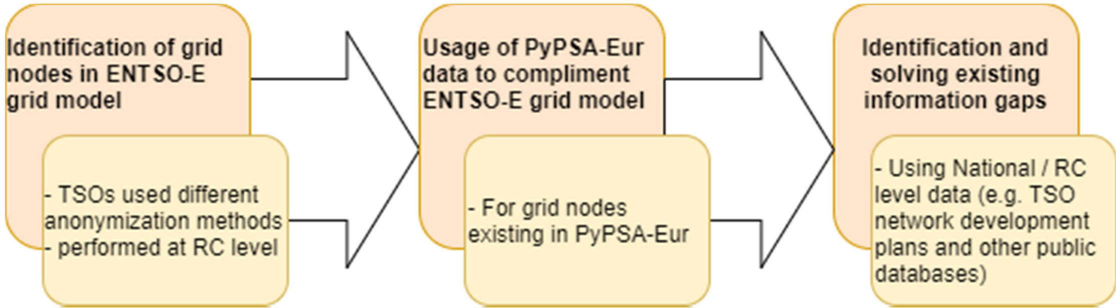


Figure 4-1 - Methodology for identification of grid nodes and inclusion of geographic information.

4.2 Generation data

Pan-EU market simulations to be performed in T4.3 require detailed information on generation resources to model the dispatch. The dispatch depends on the merit order and thereby on the costs, on the flexibility of a generation unit and on the availability. Hence, planned and forced unavailability have to be considered.

The costs can be divided into variable and fix costs. Variable costs include fuel costs, costs for CO2 emissions and further costs for operation and maintenance, e.g. costs for the transport of hard coal. Fix costs are e.g. costs for the startup of a unit. For each generation unit the fuel type is required to enable calculating the variable generation costs and the CO2 emissions. As the CO2 emissions of a generation unit also affect the variable generation costs due to the CO2 coupons costs, they also influence the merit order and thus the dispatch. The efficiency determines the relation between input and output of a generation unit and hence it is needed to calculate the operational costs. Since the efficiency is mostly unknown, the age of the plant is used to estimate the efficiency.

The flexibility of a generation unit depends on the minimum stable generation, the minimum up and down time, the ramp up and ramp down rate and the quick start capability. The minimum power is rarely known, thus it is obtained by using the age and the technology of the plant, assuming that newer plants have lower minimum power due to technical progress. Plants with a low minimum power are more flexible. The minimal turn on / turn off time determines if the unit is used as a slow base or a fast peak unit. Similar to this, the quick start capability defines if a plant can be used for the provision of control reserve even if it is turned off. More general the ramp-up / ramp-down rate is relevant for the control reserve provision, as units that are more flexible are able to make a higher contribution. Finally extreme load gradients can only be followed by very flexible storages units. As the unit commitment aims at minimizing the costs, very high startup fix costs, compensate for the typical operational concepts of nuclear or highly inflexible power plants that nearly do not leave their optimal operating point.

To obtain these data, Power Plant Matching (PPM)[18], which is an open source tool, is used. PPM is able to combine different public data sources in order to create a new coherent database. The user can define an individual geographical coverage and add further data sources.

The different data sources being used may differ in their number of units, capacity, geographical scope and level of detail. As these databases also contain different information, the challenge is to match them. The PPM tool applies a multi-step approach. In a first step the different sources are transformed into the same structure, in order to simplify the following analysis. Since many sources provide information about individual plants, in a second step the plants within one database are aggregated. Therefore, the similarity of the plants names, fuel types and geographic location is weighted pair-wise, using a naive Bayesian classification scheme. Assuming that power plants with a high similarity belong together, they are summed up and their geo-coordinates are averaged. When all individual plants are united, the separate databases are linked. For each pair of data sources a comparison based on the naive Bayesian classification scheme, which is similar to the one in step 2 is applied, creating a chain of linkages between the different sources. In order to handle conflicts between these links, each of the sources is evaluated with a reliability score depending on the refresh period. Thus, sources, which have been updated recently, get the highest score, while sources, which are not up to date get a lower score. These reliability scores are used to handle conflicts, so that data with a high score is added to the final PPM list before data from a source with a lower score. However, a power plant only occurs in the final list if it can be found at least in two separate sources, to make sure no outdated information is added [19].

The final dataset provides information on name, fuel type, country, latitude and longitude, capacity, duration (meaning the maximum state of charge capacity in terms of hours at full output capacity), commission year, last retrofit year and source, as name of the data set and project ID.

As the PPM dataset only contains information about existing power plants the RCs have to add information regarding planned power plants. For this purpose, i.e. network development plans are used.

4.3 Landscape

FlexPlan tool considers an assessment of landscape impact related to the installation of new lines. Figure 4-2 shows the work flow which will be used to assess the landscape impact. It starts from a set of candidates obtained by the FlexPlan pre-processor developed in WP2 and feed those to an optimal routing algorithm that determines the minimum cost of the candidates, taking the spatial properties of the installation into account. This helps to quantify the landscape impact on one hand, and to determine the exact technical details, such as impedance and level of partial underground especially for candidate line and cable connections for both AC and DC technology. Eventually, the cost of candidates and their technical parameters are fed into the FlexPlan tool. The detailed methodology for the optimal routing algorithm is described in [20].

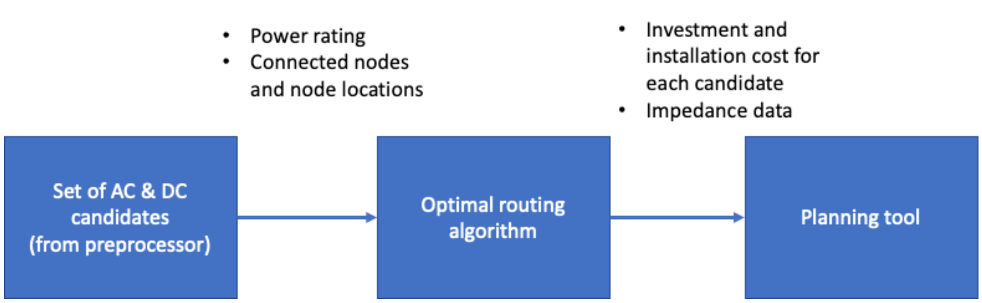


Figure 4-2 - Workflow of optimal routing algorithm.

As seen in this figure, the execution of the optimal routing algorithm and therefore the landscape impact study requires two sets of inputs: the candidates, resulting from the pre-processor tool developed in WP2, and the grid topology including the node geographic locations. Hence, this represents an additional data need: the location of the different grid nodes. As all nodes can be selected as candidate nodes, this information is required for all nodes. The geographic information of grid nodes is already identified as a data need and the existing data sources and approach to include this information in the grid model is described in section 4.1. No additional data needs are currently identified or foreseen to perform the landscape impact studies.

4.4 Air quality

The impact on air quality to be performed in the FlexPlan scope is limited to thermal generation and it follows the overall approach depicted in Figure 4-3.

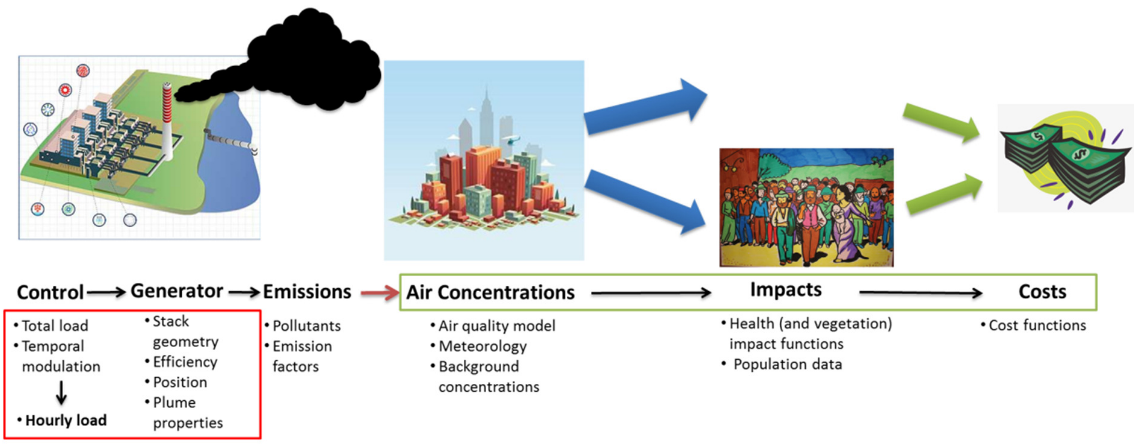


Figure 4-3 - Conceptual model for air quality impact evaluation.

This methodology creates a simplified air quality model for each generator in order to define a linear relationship between emission rates and air quality concentration. The simplified model, depends on:

- Generator features: Stack geometry, Plume properties (e.g. flow rate, temperature and velocity);
- Background concentrations: representing the air quality concentrations due to all the other sources affecting the domain;
- Meteorology.

The simplified air quality model is expressed in terms of a linear relationship, therefore based on a simple coefficient that represent the link between the emission rate and the corresponding air quality concentration. By means of the simplified model the air quality concentration can be derived for each hour, pollutant, year and generator. The air quality concentration represents the main input for the impact functions that allow computing the effect of air pollution on health. To execute this methodology, the set of data present in Table 4-1 is required.

	Attribute	Unit	Comments
	Generator ID	[-]	
	coordinates	[Lat/Lon]	geographical position is essential to compute air quality impacts
	Annual total emissions	[tons/year]	for each pollutant (SO2, NOx, VOC, CO, NH3, PM10 and PM2.5)
	emission factor	[kg/MJ]	for each pollutant (SO2, NOx, VOC, CO, NH3, PM10 and PM2.5)
	reference yearly profile	[MJ/hour]	for a whole year. A "reasonable" operational temporal profile to be used as Base state for the simplified model
Used to compute the so called "plume rise"	Stack height	[m]	
	Stack diameter	[m]	
	Stack Flow Rate	[m3/s]	Flue gas flow rate
	Stack Exit Velocity	[m/s]	Flue gas velocity
	Stack Exit Temperature	[°K]	Flue gas temperature
	Generator fuel type	[-]	In case additional rules based on type needed
	Efficiency	MJ/ton	Energy produced by fuel mass unit
	emission factor	Kg/ton	Pollutant emission (mass) by fuel consumption (mass)

Table 4-1 - Data needs for air quality modelling.

The set of parameters necessary to compute the plume rise is the only data, which represent a challenge, as it might be impossible to obtain. These are specific for each thermal unit and usually not released to public. Hence, and as an alternative, these can be replaced by the information of the Type of Generator and installed capacity. This data is already identified and the corresponding data source is described in section 4.2. The data related to the geographic location was already discussed as well. Regarding the different parameters related to emissions, if there is no information for each pollutant, then the overall emissions will be considered and these will be divided into the different pollutants according to average values taking into account the thermal unit type.

4.5 Carbon footprint

Evaluating the carbon footprint of a product or a service means calculating all the emission of greenhouse gases occurring during the entire life cycle of the analysed product/service. Emissions are accounted in terms of their potential effect on climate, called Global Warming Potential, which is measured as kg of carbon dioxide equivalent (kg CO2eq). In Figure 4-4 a schematic representation of the carbon footprint of electricity production is represented.

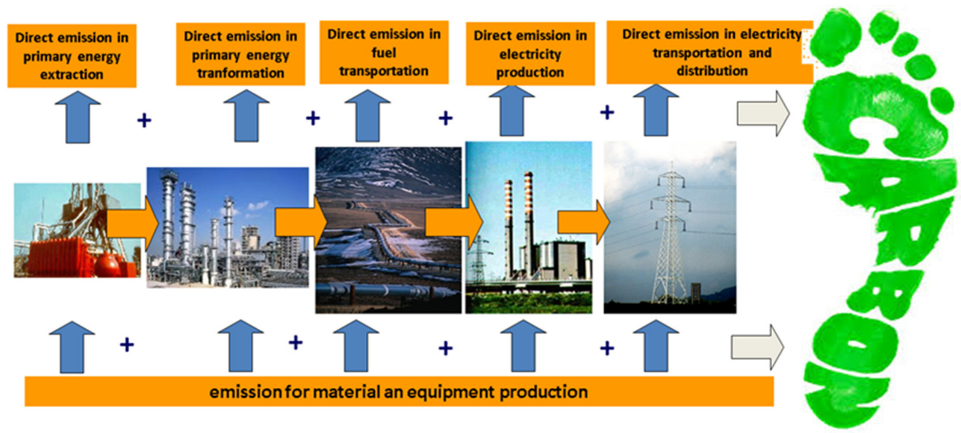


Figure 4-4 - Schematic description of the electricity production carbon footprint.

Keeping in mind the general goal of the FlexPlan project, the approach for the inclusion of candidate options carbon footprint in the planning tool will be limited to the differences among different options, without considering the carbon footprint of common elements among candidates, such as the carbon footprint of the existing network. The carbon footprint of each candidate can be expressed as the sum of the carbon footprint of energy production and the carbon footprint of grid components. The considered grid components in this framework are: new lines, new storage system, new HVDC converter and Phase Shifter transformer. Since new generators are not considered as candidates for the FlexPlan tool, for sake of simplicity, the carbon footprint evaluation will not consider the power plant construction and decommissioning. This means that carbon footprint of enabled energy production will be limited to the electricity produced by thermal power plants, as far as the carbon footprint of electricity production from non-thermal renewable power plants (wind, solar, hydro) are mainly due to power plant construction and decommissioning. Keeping in mind the life cycle perspective of the carbon footprint concept, we will consider the emission due to energy source extraction (including biomass cultivating), to fuel production and to fuel combustion in the power plant. The foreseen data needs to perform this analysis are given in Table 4-2. These are only related to thermal generation units as data related to grid components is a result of the candidate selection process.

Attribute	Unit	Comments
Generator ID	[-]	
Generator fuel type	[-]	According to EUSTAT classification
Generator efficiency	MJ/kwh	Considering 1kwh el out = 1 kw th out for CHP plant
Generation	kWh	For the candidate option
Generator biomass type	[-]	Only for biomass using generators specify kind of biomass: solid-gaseous-liquid, if it is residual or not, and for cultivated biomass type of Crops (palm, rape, soybean…)

Table 4-2 - Carbon Footprint data needs.

These data requirements are also fulfilled using the generation related data, described in section 4.2.

4.6 Cost related data

The regional cases execution will consider the evaluation of different candidates for grid expansion. These include traditional grid expansion measures together with the utilization of flexibility related solutions. The analysis performed and the evaluation of different candidates includes a techno-economic evaluation. Hence, for this purpose, it is necessary to take into consideration existing costs for the considered technologies. It is important to mention that costs are different for different technologies and additionally, different geographies might have different costs for the same technology, resulting in an analysis at regional case level.

Cost related data can be agglomerated into three different categories, each one with specific characteristics.

- Flexibility solutions costs: these are object of literature review and projections for costs of technologies (e.g. evolution of battery costs);
- Transmission grid expansion costs: these are related to traditional expansion measures of transmission assets (e.g. building new lines). These costs are available in public documentation related to TSOs network development plans. Additionally, reference values can also be found at [21];
- Distribution grid expansion costs: these are related to costs of technologies used in distribution systems. In this case, data is not usually publicly available (as it is in transmission systems). However, there is still some information available, as reference values can be found at[22].

5 Conclusions

This document contains the description of datasets collected and created in the scope of FlexPlan project. FlexPlan sets forward an ambitious plan to develop an innovative grid-planning tool and demonstrate its capabilities through six regional cases that cover almost all Europe. The execution of these six regional cases, together with a prior pan-European level simulation work ensuring continuity and coherence among the regional cases, represents a complex data collection and processing activity, performed in the scope of Tasks 4.1 and 4.2. The data collected and presented in this report is organized into three main categories: pan-European scenarios, grid data and complementary datasets.

FlexPlan will include a set of simulations in six regional cases. Together, these represent a larger part of Europe. Thus, the simulation of these regional cases corresponds globally to data collection at pan-European level. The six regional cases will be developed considering three target years, 2030, 2040 and 2050, demonstrating the FlexPlan tool capability to deal with multi-decade grid planning strategies. Additionally, each one of these target years considers three different scenarios, resulting in nine scenarios to be simulated by each one of the regional cases. These scenarios represent three very different realities in terms of future power grids, yet they aspire to the same ambitious climate targets. In order to have a coherent and realistic validation of the tool, the chosen scenarios are based on those presented in TYNDP 2020 study, currently under development by the ENTSOs. The methodology used to develop these scenarios is herein described. For 2030 and 2040 target years, FlexPlan scenarios are purely based on TYNDP 2020 ones, with some data corrections and adaptations whenever needed to ensure a proper development of the models to be simulated and when some data is not directly available. These adaptations are validated with TYNDP 2018 data, to ensure a coherent approach with ENTSO-E network development plans. 2050 scenarios are also based on the macroscopic vision given by the ENTSOs in the current network development plan. However, since the data for this target year is not yet available, FlexPlan developed a methodology which is based on TYNDP 2020 macroscopic vision, validating the obtained results with A Clean Planet for All strategy by the European Commission. The utilization of these two well-known and accepted data sources ensure that FlexPlan scenarios for the three target years are aligned with current strategies being delineated and put in place all around Europe.

The pan-European scenarios data are mainly related to generation and load forecasts/visions for the three target years but, in order to validate the FlexPlan tool, a full detailed grid model is needed. As one of the goal of the project is also to demonstrate transmission and distribution development planning, this means that these grid models have to include both: transmission and distribution grids. For transmission grids, the team decided to use ENTSO-E 2018 Grid Dataset, as this is the most recent one available. This model was used in the scope of TYNDP 2018 and covers all continental Europe, allowing the team to separate the grid into the different regional cases (6 RCs) while ensuring a coherence among the different grids through a realistic representation of existing interconnections and equivalent models. This dataset is complemented with an open-source grid model – PyPSA-Eur – which is used in the Nordic regional case where data is not available from the ENTSO-E model. Regarding distribution networks, FlexPlan is developing a methodology, which allows to create synthetic networks based on realistic statistics, resulting in a grid model which is similar to real distribution systems. The usage of these two models combined, creating a T&D grid model, will result in complex grid models at regional case levels, fully demonstrating the capabilities of the developed tool.

Finally, the data collected includes another heterogeneous datasets, ensuring a maximum reach of solutions demonstration at regional case levels. These data include generation related data, with the usage of an open-source database – powerplantmatching – to obtain all required characteristics from current and planned power plants, ensuring that the pan-European scenarios are coherently cascaded into existing generation units. Since FlexPlan deals with different vectors of grid planning, and landscape and environmental impacts are also considered, the grid models are complemented with geographic location information of all grid nodes. This also represents a sound effort, taking into consideration the amount of nodes existing in the different regional cases.

In summary, FlexPlan Tasks 4.1 and 4.2 are related to data collection and harmonization activities. This document contains the description of all data collected in the project scope. These data is organized in three main categories: pan-European Scenarios, grid models and additional datasets (e.g. generation units information and geographic location of grid nodes). These data allows to first perform pan-European simulations, which will be deal with next, in the scope of tasks 4.3 and 4.4 and later on, all these data will be combined in the simulation of the six regional cases designed to demonstrate the full capabilities of the FlexPlan grid planning tool.

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Appendix A – Description of MILES

The market and network simulation environment MILES enables techno-economic analyses of the pan-European energy system and covers the entire process chain of network development planning.

First of all, the forecasted capacities of RES and the electrical and thermal load are regionally located sector-specifically for the considered market areas. Time series are then generated on the basis of historical consumption and weather data for all electrical and thermal loads and for all types of renewables, taking into account peak capping where appropriate. Depending on the heat demand time series, the use of heat-controlled CHP plants with a low output range is then derived and must-run requirements for large, current-controlled power plants with heat extraction are set. To smooth the resulting residual load, the operation of flexibility options, such as load shifting (DSM) or the operation of power-to-heat and PtG plants, can be simulated as an option.

Subsequently, the cost-minimum use of conventional power plants and storage facilities in Europe is determined for a planning year with the help of a power plant deployment optimization, typically with an hourly resolution. The underlying market coupling can either be exclusively NTC-based, purely power flow-based or also designed as a hybrid system. In addition to the schedules of conventional power plants and storage facilities, the simulation also shows the exchange services between the market areas under consideration. In addition, it is shown to what extent the supply of power from supply-dependent generation plants has to be reduced due to limited transfer and storage capacities (so-called non-usable power).

A.1 Module Description

A.1.1 Regionalisation

Due to the energy revolution WTGs, PV systems and the location of electrical loads are the main drivers in the future energy system. To regionalize the installed capacity of these, the territory has to be structured according to the local conditions.

Regionalisation factors

Areas with high energy potential and thus high feed-in of RES are identified using wind speed and solar irradiation. With this information regionalization factors can be determined, describing the percentage of the total installed capacity which is installed in the respective region. There are two kinds of regionalization factors: one-dimensional and multi-dimensional factors. One dimensional factors need one set of input data. To calculate a multi-dimensional regionalization factor a main parameter and a weighting factor are needed. Using wind energy as an example, a one dimensional factor would be the relation of agricultural area in the region compared to the whole agricultural area in the country. For a two dimensional factor the first factor (agricultural area) could be weighted with the potential energy yield in the area. As a result, more plants would be installed in areas with higher average wind speed. The electrical load has to be distinguished between load of households, industry and services. For instance for the household sector the population is used as a major parameter.

In the following, the time series determination of photovoltaic systems and WTGs and power plant deployment optimisation are presented in more detail. In addition to a description of the individual models, an explanation of the parameterisation is also given.

A.1.2 Time series determination of WTGS and PV systems

Based on the installed renewable energy determined within the scope of regionalisation, the feed-in time series of the respective energy sources are determined. The procedure for determining the feed-in time series of WTGs and PV plants is described below.

Weather data

To determine the time series, meteorological data from the COSMO-EU model of the German Weather Service are used [23]. The time series of wind speed and solar radiation are used as well as information on the temperature at 2 m and 116 m altitude and the albedo of the ground. The data are available for a grid with a mesh size of 7 km throughout Europe. The grid points closest to the electric grid nodes are used for that.

Standardized power supply of the WTG

For each grid node the time series of the standardised feed-in power of a WTG is calculated using the time series of wind speed. The power curve of a WTG is determined by varying the wind speed at the height of the hub v_{hub} and under addition of the rotor surface A_{R} of the characteristic value of the plant (coefficient of power) c_P and the local air density ρ_L is calculated according to [24] as follows:

$$P(v_{\text{Nabe}}(t)) = 0{,}5 \cdot \rho_{\text{L}} \cdot A_{\text{R}} \cdot c_P(v_{\text{hub}}(t)) \cdot v_{\text{hub}}^3(t)$$

The characteristic curve used describes the performance of an average WTG on the basis of its coefficient of performance according to the current state of the art (see [25] for derivation). The characteristic curve is shown in the figure A.1 compared to 47 characteristic curves of the WTGs from [26], which were used for its derivation.

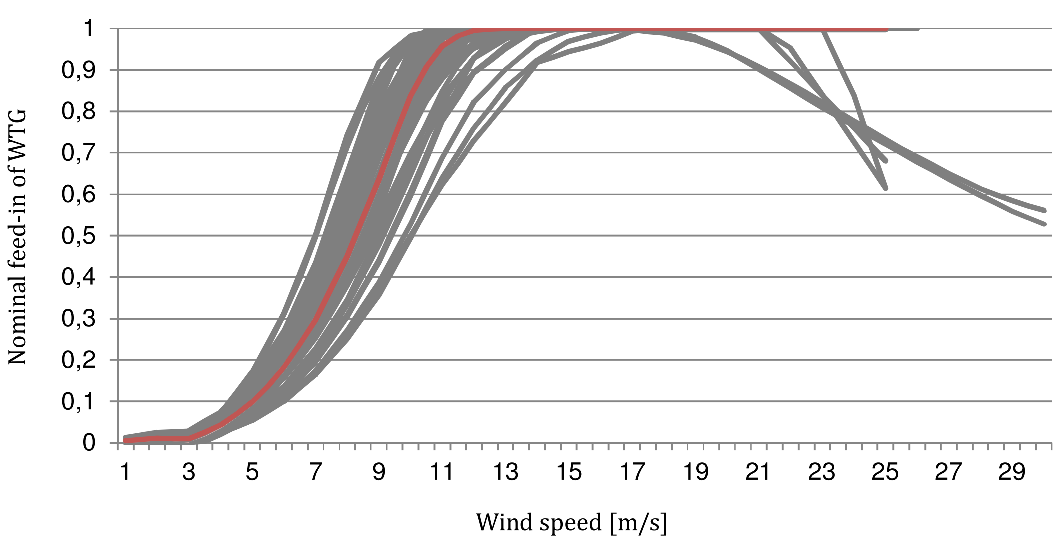

Figure A-1 Comparison of the used characteristic curve with the characteristic curves of other WTGs (source [26]).

The simulated plants do not have storm control, but a storm shutdown. In concrete terms, this means that the turbines switch off at wind speeds above 25 m/s and do not provide any electrical power. On the basis of the standardised power curve, the wind speed can be transferred to the standardised feed-in of a WTG at any node and at any time.

Standardized power supply of the PV plant

The standardized feed-in power of a PV plant is calculated on the basis of the time series of the global irradiance at each network node. The global irradiance describes the irradiance on a horizontal surface [27]. Since PV plants are erected at a certain angle of inclination, the irradiance on the module does not correspond to the global irradiance. The conversion is done by breaking down the global irradiance into a direct and a diffuse part. Furthermore, a reflected portion is taken into account. The determination of the direct, diffuse and reflected portion is done according to [27] and is not explained in detail here.

With the resulting time series of irradiance on the inclined plane $E_{\mathrm{gen}}(t)$ the feed-in power of the PV system is derived according to [27] For this purpose, the standardized, hourly ideal feed-in is $P_{\mathrm{norm,ideal}}(t)$ calculated.

$$P_{\mathrm{norm,ideal}}(t) = \frac{E_{\mathrm{gen}}(t)}{1000 \frac{\mathrm{W}}{\mathrm{m}^2}}$$

The ideal hourly feed-in neglects, among other things, power losses due to dirt, snow, shading or efficiency reductions in partial load operation. All these losses are taken into account in the performance ratio PR in summary. According to [27] this is for very good plants $PR = 0{,}8$ and for good investments with $PR = 0{,}75$ while **for bad plants it can be** $PR \leq 0{,}6$. According to [28], PV plants in southern Germany achieve a feed-in of up to 85 % of their nominal capacity in one grid area. The performance ratio is initially neglected at this point, as the losses it depicts are also depicted using a correction factor explained below.

The dependence of the feed-in power on the module temperature is specially taken into account. The module temperature $T_{\mathrm{M}}(t)$ can be calculated from the ambient temperature $T_{\mathrm{U}}(t)$, the irradiance $E_{\mathrm{gen}}(t)$ and a constant of proportionality c according to [27],. The constant of proportionality c depends on the module installation and varies between 22°C for completely free mounting and up to 55°C for facade integration without rear ventilation. According to [27], this assumption describes a roof-integrated installation with poor rear ventilation. In [28] this coefficient is taken as the average nominal operating temperature.

$$T_{\mathrm{M}}(t) = T_{\mathrm{U}}(t) + c \cdot \frac{E_{\mathrm{gen}}(t)}{1000 \frac{\mathrm{W}}{\mathrm{m}^2}}$$

The deviation of the module temperature from the standard test conditions (module temperature 25°C) is used to determine the effect on the performance of the PV system. The power change due to the temperature deviation is described by the temperature change coefficient. According to [27], this is -0.4 % per °C for silicon solar cells. The coefficient of change in output of the PV plant due to the change in module temperature $k_{\mathrm{T}}(t)$ can therefore be described as follows:

$$k_{\mathrm{T}}(t) = -0{,}4\%/°\mathrm{C} \cdot (T_{\mathrm{M}}(t) - 25°\mathrm{C})$$

This results in the standardized feed-in power of a PV system $P_{\mathrm{norm,real}}(t)$ ultimately as follows:

$$P_{\mathrm{norm,real}}(t) = PR \cdot (1 + k_{\mathrm{T}}(t)) \cdot \frac{E_{\mathrm{gen}}(t)}{1000 \frac{\mathrm{W}}{\mathrm{m}^2}}$$

Correction factors for WTGS and PV plants

If the power supply of all WTGs and PV systems is reproduced for historical years using the methods described above, the calculated energy supply is higher than the real values published in [29] and [30]. This is due to various effects which have an influence on the power supply and cannot be fully taken into account in the modelling. For example, downtimes due to maintenance, power adjustment due to grid bottlenecks or air turbulence in large wind farms cannot be represented in detail when calculating the feed-in of the WTGs. In the case of PV plants, these include the consequences of pollution, snow, shading or a reduction in efficiency due to partial load operation, as mentioned above. There is also the assumption that the weather data of the COSMO-EU model are above the actual values and the energy supply is thus overestimated (see [31]). For these reasons, the power supply of the plants is adjusted by a correction factor.

The correction factor depends on the selected weather year. A correction factor is determined for each technology for each month of the year. To derive the correction factors, the hourly power supply is determined for all WTGs and PV systems installed according to [32].This is based on the time series of regional wind speed and global radiation according to the methodology explained above. By balancing the time series of all nodes and integrating the resulting total feed-in time series, the monthly energy supply of the plants is calculated. This energy supply is now compared with the energy actually supplied according to[29].

For PV systems, the correction factor is the ratio of the real injection of all PV plants to the simulated injection of the ideal PV system. In the case of WTGs, the application of the correction factor to the feed-in time series does not make sense, since feed-in peaks would be scaled lower in this case. This would significantly distort the consequences of peak capping. Therefore the correction factor is applied to the wind speed time series. The calculation is carried out iteratively: The correction factor is reduced from 100 % until the simulated energy supply of all plants in the month under consideration corresponds to the real feed-in or, for future scenarios, to the assumed full-use hours.

A.1.3 Power plant optimisation

Model description

The developed power plant deployment optimization is a so-called Security Constrained Unit Commitment Model, which is formulated as a Mixed-Integer Linear Program (MILP).

The optimisation aims at determining the cost-minimised use of conventional power plants and storage facilities to cover the electrical load and the reserve power to be maintained, taking into account the RES injection, the available transmission capacities between the market areas and the technical, partly time-coupling restrictions of the generation units and storage facilities. The technical constraints taken into account include minimum and maximum power, unavailability, minimum downtimes and minimum operating times, power gradients (during operation and during start-up and shut-down processes), maximum turbine and pumping capacities as well as maximum storage capacities.

The limited transmission capacities between the market areas under consideration can be taken into account in power plant deployment optimization using various capacity models.

The formulated optimization problem is solved using a rolling approach. For this purpose, the year under consideration is divided into overlapping intervals of constant width, which represent the planning horizons of the market participants. These time intervals are optimized sequentially, whereby the determined system state in a fixed time step of the preceding interval serves as the initial state for the following optimization interval. In addition, a pre-simulation is carried out to generate a steady state of the system directly at the beginning of the year under consideration. The time window simulated for this purpose corresponds to the last time steps of the analysis year.

From the already mentioned results of the optimization (schedules of conventional power plants and storage facilities, trade flows between market areas, non-usable power), the trading prices of the individual market areas as well as the overall economic costs of energy supply (the electricity generation costs of the entire system) can be derived. In addition, the greenhouse gas emissions in the market areas under consideration can be determined on the basis of the energy quantities provided.

The formulated sum condition is as follows:

$$\sum_{s \in M_{s,i}} \sum_{g \in M_{g,\mathrm{DE}}} \frac{P_{g,s} \cdot \epsilon_k}{0{,}278 \frac{\mathrm{MWh}}{\mathrm{GJ}} \cdot \eta_g} \quad \leq \quad E_{i,\mathrm{DE}}$$

With:

- $P_{g,s}$: generation of power plant g (of type k) in hour s [MWh]
- ϵ_k: specific emissions of the power plant type k [t/GJ]
- η_g: specific emissions of the power plant type g (of type k)
- $E_{i,\mathrm{DE}}$: maximum permissible CO_2 emissions of the German electricity sector in optimization interval i
- $M_{s,i}$: quantity of all hours of the optimization interval i
- $M_{g,\mathrm{DE}}$: quantity of all German power plants

Appendix B – Net Transfer Capacities (NTCs) (source TYNDP 2020)

NT-2030

NTC [MW] ↓From / To →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
Albania										250					500	350									650											
Belgium							1000		2800		1000						2400																	680		
Bosnia-Herzegovina														750		800									600											
Bulgaria										1350					500							1200			400											900
Denmark West						590	3500				1400						700	1640					740													
Denmark East					600		585																1700													
Germany		1000			3500	600			3000		1400						5000	1400	5400	2000			615	2700					1500					2300		
Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
United Kingdom		1000			1400		1400		4000			500					1000	2800																		
Ireland											500																									
Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
Norway					1640		1400				2800						700						3695													
Austria							5400						680											1200			950		900	800						
Poland							3000																600			990			800				500			
Portugal																												3500								
Romania				1100																					1000					1100					150	
Sweden					680	1300	615	3200										3995		600													700			
Switzerland							4600		1300				3750						1200																	
Serbia	500		600	400										500	650	600						800								600						
Slovakia																				990									1100	2600					400	
Slovenia													600	2000					950											1200						
Spain									5000												4200															
Czech Republic							2100												900	600						1800										
Hungary														1700					800			1000			600	1800	1200								450	
Estonia								1016																								1100				
Latvia																															900		950			
Lithuania																				500			700									950				
Luxembourg		180					2300																													
Ukraine																						150				400				650						
Turkey				500						580																										

NT-2040																																				
NTC [MW] ↓**From / To** →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
Albania										250					500	350									650											
Belgium							1000		2800		1000						2400																	680		
Bosnia-Herzegovina														750		800									600											
Bulgaria										1350					500							1200			400											900
Denmark West						590	3500				1400						700	1640					740													
Denmark East					600		585																1700													
Germany		1000			3500	600			3000		1400						5000	1400	5400	2000			615	2700					1500					2300		
Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
United Kingdom		1000			1400		1400		4000			500					1000	2800																		
Ireland											500																									
Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
Norway					1640		1400				2800						700						3695													
Austria							5400						680											1200			950		900	800						
Poland							3000																600			990			800				700			
Portugal																												3500								
Romania				1100																					1000					1100					150	
Sweden					680	1300	615	3200										3995		600													700			
Switzerland							4600		1300				3750						1200																	
Serbia	500		600	400										500	650	600						800								600						
Slovakia																				990									1100	2600					400	
Slovenia													600	2000					950											1200						
Spain									5000												4200															
Czech Republic							2100												900	600						1800										
Hungary														1700					800			1000			600	1800	1200								450	
Estonia								1016																								1100				
Latvia																															900		950			
Lithuania																				700			700									950				
Luxembourg		180					2300																													
Ukraine																						150				400				650						
Turkey				500						580																										

FlexPlan

NT-2050

NTC [MW] ↓From / To →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
Albania										250					500	350									650											
Belgium							1000		2800		1000						2400																	680		
Bosnia-Herzegovina														750		800									600											
Bulgaria										1350					500							1200			400											900
Denmark West						590	3500				1400						700	1640					740													
Denmark East					600		585																1700													
Germany		1000			3500	600			3000		1400						5000	1400	5400	2000			615	2700					1500					2300		
Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
United Kingdom		1000			1400		1400		4000			500					1000	2800																		
Ireland											500																									
Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
Norway					1640		1400				2800						700						3695													
Austria							5400						680											1200			950		900	800						
Poland							3000																600			990			800				700			
Portugal																												3500								
Romania				1100																					1000					1100					150	
Sweden					680	1300	615	3200										3995		600													700			
Switzerland							4600		1300				3750						1200																	
Serbia	500		600	400										500	650	600						800								600						
Slovakia																				990									1100	2600					400	
Slovenia													600	2000					950											1200						
Spain									5000												4200															
Czech Republic							2100												900	600						1800										
Hungary														1700					800			1000			600	1800	1200								450	
Estonia								1016																								1100				
Latvia																															900		950			
Lithuania																				700			700									950				
Luxembourg		180					2300																													
Ukraine																						150				400				650						
Turkey				500						580																										

FlexPlan

NTC [MW] ↓From / To →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
DE-2030																																				
Albania										250					500	350									650											
Belgium							1000		2800		1000						2400																	680		
Bosnia-Herzegovina														750		800									600											
Bulgaria										1350					500							1200			400											900
Denmark West						590	3500				1400						700	1640					740													
Denmark East					600		585																1700													
Germany		1000			3500	600			3000		1400						5000	1400	5400	2000			615	2700					1500					2300		
Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
United Kingdom		1000			1400		1400		4000			500					1000	2800																		
Ireland											500																									
Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
Norway					1640		1400				2800						700						3695													
Austria							5400						680											1200			950		900	800						
Poland							3000																600			990			800				700			
Portugal																												3500								
Romania				1100																					1000					1100					150	
Sweden					680	1300	615	3200										3995		600													700			
Switzerland							4600		1300				3750						1200																	
Serbia	500		600	400										500	650	600						800								600						
Slovakia																				990									1100	2600					400	
Slovenia													600	2000					950											1200						
Spain									5000												4200															
Czech Republic							2100												900	600						1800										
Hungary														1700					800			1000			600	1800	1200								450	
Estonia								1016																								1100				
Latvia																															900		950			
Lithuania																				700			700									950				
Luxembourg		180					2300																													
Ukraine																						150				400				650						
Turkey				500						580																										

DE-2040

NTC [MW] ↓From / To →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
Albania										250					500	350									650											
Belgium							2000		2800		1000						2400																	680		
Bosnia-Herzegovina														750		800									600											
Bulgaria										1350					500							1200			400											900
Denmark West						590	3500				1400						700	1640					740													
Denmark East					600		585																1700													
Germany		2000			3500	600			3000		1400						5000	1400	5400	2000			615	2700					1500					2300		
Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
United Kingdom		1000			1400		1400		4000			500					1000	2800																		
Ireland											500																									
Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
Norway					1640		1400				2800						700						3695													
Austria							5400						680											1200			950		900	800						
Poland							3000																600			990			800				700			
Portugal																												3500								
Romania				1100																					1000					1100					150	
Sweden					680	1300	615	3200										3995		600													700			
Switzerland							4600		1300				3750						1200																	
Serbia	500		600	400										500	650	600						800								600						
Slovakia																				990									1100	2600					400	
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Czech Republic							2100												900	600						1800										
Hungary														1700					800			1000			600	1800	1200								450	
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Latvia																															900		950			
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Ukraine																						150				400				650						
Turkey				500						580																										

FlexPlan

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NTC [MW] ↓From / To →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
Albania										250					500	350									650											
Belgium							2000		2800		1000						2400																	680		
Bosnia-Herzegovina														750		800									600											
Bulgaria										1350					500							1200			400											900
Denmark West						590	3500				1400						700	1640					740													
Denmark East					600		585																1700													
Germany		2000			3500	600			3000		1400						5000	1400	5400	2000			615	2700					1500					2300		
Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
United Kingdom		1000			1400		1400		4000			500					1000	2800																		
Ireland											500																									
Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
Norway					1640		1400				2800						700						3695													
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Sweden					680	1300	615	3200										3995		600													700			
Switzerland							4600		1300				3750						1200																	
Serbia	500		600	400										500	650	600						800								600						
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Latvia																															900		950			
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Luxembourg		180					2300																													
Ukraine																						150				400				650						
Turkey				500						580																										

FlexPlan

GA-2030

NTC [MW] ↓From / To →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
Albania										250					500	350									650											
Belgium							1000		2800		1000						2400																	680		
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Denmark West						590	3500				1400						700	1640					740													
Denmark East					600		585																1700													
Germany		1000			3500	600			3000		1400						5000	1400	5400	2000			615	2700					1500					2300		
Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
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Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
Norway					1640		1400				2800						700						3695													
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Switzerland							4600		1300				3750						1200																	
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Turkey				500						580																										

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NTC [MW] ↓From / To →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
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Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
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Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
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Hungary														1700					800			1000			600	1800	1200								450	
Estonia								1016																								1100				
Latvia																															900		950			
Lithuania																				700			700									950				
Luxembourg		180					2300																													
Ukraine																						150				400				650						
Turkey				500						580																										

GA-2050																																				
NTC [MW] ↓From / To →	Albania	Belgium	Bosnia-Herzegovina	Bulgaria	Denmark West	Denmark East	Germany	Finland	France	Greece	United Kingdom	Ireland	Italy	Croatia	Macedonia	Montenegro	Netherlands	Norway	Austria	Poland	Portugal	Romania	Sweden	Switzerland	Serbia	Slovakia	Slovenia	Spain	Czech Republic	Hungary	Estonia	Latvia	Lithuania	Luxembourg	Ukraine	Turkey
Albania									250					500	350									650											
Belgium							1000		2800		1000						2400																	680		
Bosnia-Herzegovina														750		800									600											
Bulgaria										1350					500							1200			400											900
Denmark West						590	3500				1400						700	1640					740													
Denmark East					600		585																1700													
Germany		1000			3500	600			3000		1400						5000	1400	5400	2000			615	2700					1500					2300		
Finland																							3200								1000					
France		4300					3000				4000		4100											3700				5000						380		
Greece	250			800									500		1100																					660
United Kingdom		1000			1400		1400		4000			500					1000	2800																		
Ireland											500																									
Italy									2000	500						600			500					1700			650									
Croatia			700																						500		2000			1700						
Macedonia	500			400						850															400											
Montenegro	350		750										600												600											
Netherlands		2400			700		5000				1000							700																		
Norway					1640		1400				2800						700						3695													
Austria							5400						680											1200			950		900	800						
Poland							3000																600			990			800				700			
Portugal																												3500								
Romania				1100																					1000					1100					150	
Sweden					680	1300	615	3200										3995		600													700			
Switzerland							4600		1300				3750						1200																	
Serbia	500		600	400										500	650	600						800								600						
Slovakia																				990									1100	2600					400	
Slovenia													600	2000					950											1200						
Spain									5000												4200															
Czech Republic							2100												900	600						1800										
Hungary														1700					800			1000			600	1800	1200								450	
Estonia								1016																								1100				
Latvia																															900		950			
Lithuania																				700			700									950				
Luxembourg		180					2300																													
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Turkey				500						580																										