e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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Document information

General purpose

This document is the deliverable 'D4.3 – Data sets of scenarios and intermediate grid architectures for 2040' of the e-Highway2050 project. Its task is to identify the most plausible energy scenarios and grid architectures for 2040 linking the four visions of ENTSO-E's *Ten Year Network Development Plan* for 2030 and the five e-Higway2050 scenarios for 2050.

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Change status

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V1.3	2015-10-16	Conclusion, add list of tables and figures.	R. Pestana
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EXECUTIVE SUMMARY

This deliverable report describes the methodology and the results of task 4.3, whose objectives are to propose energy scenarios and intermediate grid architectures for the year 2040. In this context, task 4.3 aims to an efficient implementation of grid reinforcements between 2030 and 2050, thus forming the modular development plan between these decades.

The challenge in this task is to ensure consistency with the work developed in e-Highway2050 for 2050 and with the current plans for 2030, developed by ENTSO-E in the *Ten Year Network Development Plan* (TYNDP). Furthermore, this task aims at finding common solutions which are consistent with the variety of future scenarios for 2030 and 2050.

2040 Scenarios

The first part of this task deals with the development of energy scenarios for the year 2040. These scenarios describe the demand and generation at different spatial and temporal levels. In this way, figures for the different installed generating capacities and also hourly time series for the load and renewable generation can be derived. This process takes into account the figures for annual demand and installed generating capacities for 2030 and 2050. By considering the four 2030 visions from the TYNDP 2016 draft and the five 2050 scenarios from e-Highway2050, a qualitative and quantitative comparison of the possible evolution of demand and generation is carried out in order to select a single 2030 vision for each 2050 scenario. The resulting path from 2020 to 2050 is presented in Figure 1, including a likely origin in 2030 for each scenario.

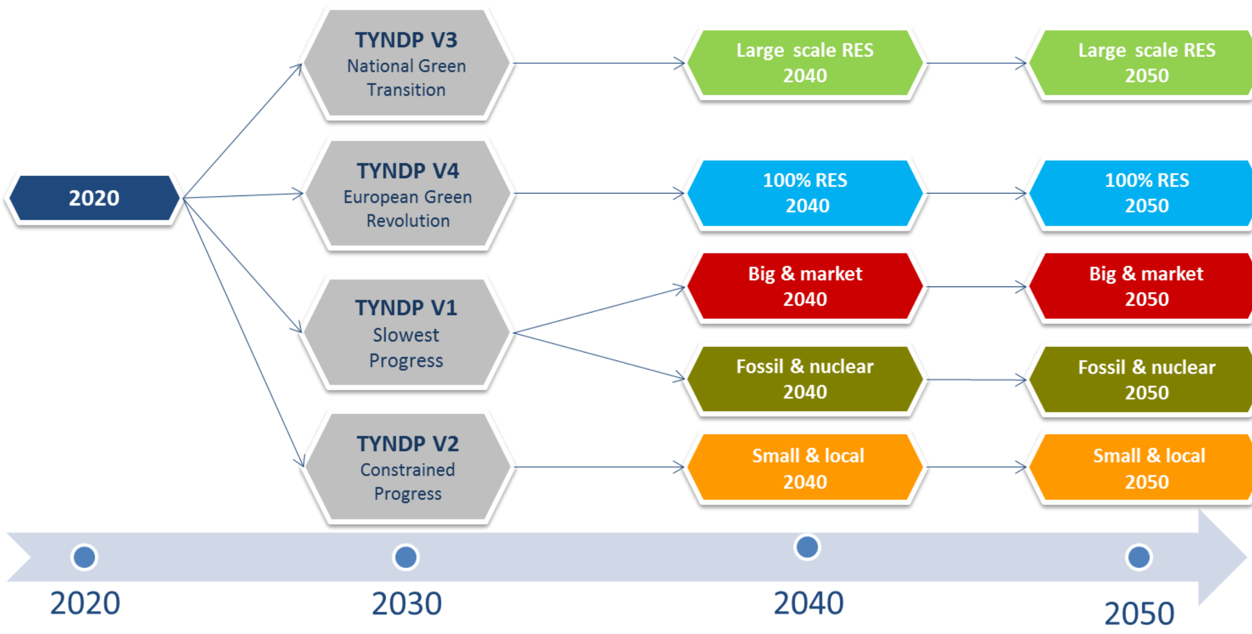

Figure 1: 2040 Scenarios - from 2020 to 2050

In a next step, the quantification of the 2040 scenarios is done on country level by interpolating the assumptions for generation, storage and demand between the 2030 visions and the 2050 scenarios. For this purpose, additional assumptions are used to allow the estimation of data, which is not provided by the TYNDP. In a subsequent step, adequacy simulations are performed in order to adapt the number of thermal plants. These simulations are not considering grid constraints, but instead infinite transmission capacities between all areas. This step is in line with the work carried out for 2050. However, the assessment of the system's adequacy in 2050 showed a need for additional peaking units to cover the demand while the opposite situation is found in 2040, where the generation has a too high flexibility in terms of missing adequacy indicators. For this reason, the development process employed for 2040 is trying to reach the same level of adequacy in order to aim for a uniform grid expansion between 2030 and 2050. This is done by decreasing parts of the flexible generation in 2040 in an automatic iterative process.

The last step of the scenario quantification consists of the distribution of country data to clusters, which are the smallest entities in system simulations. This work is done with the help of distribution keys, originally developed during the quantification of the scenarios for 2050. Through the determination of the cluster data, system simulations are performed on cluster level. The resulting energy mix for all scenarios in 2040 is presented in Figure 2.

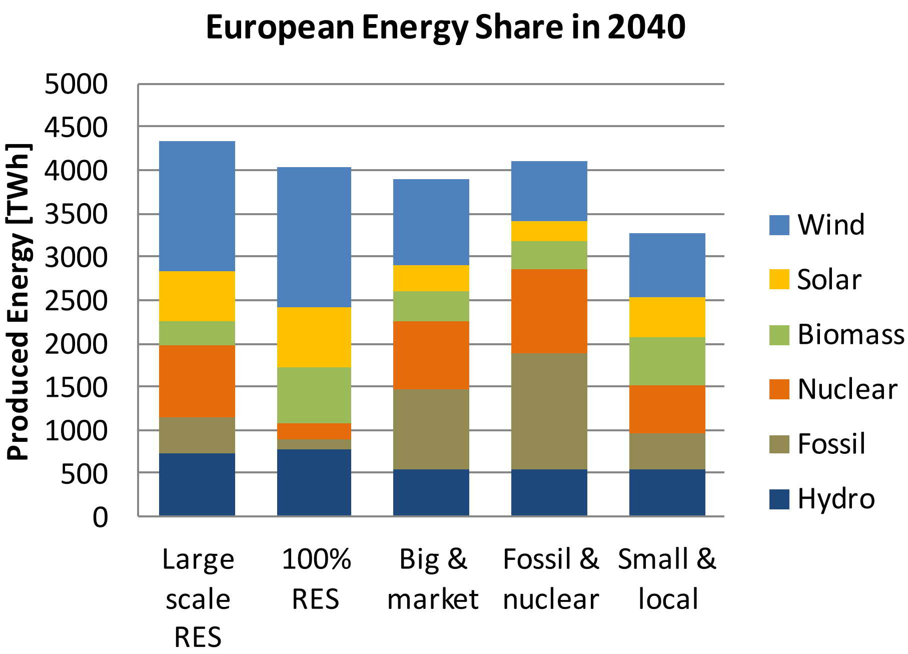

Figure 2: European energy mix in all scenarios in 2040 (including imports from North Africa)

It can be noted that the energy share in 2040 is already in line with the targeted energy mix for 2050 in each scenario. That said the scenarios *Large Scale RES* and *100% RES* show already a very high share of renewable generation in 2040. The envisaged installation of photovoltaics and wind capacities is significant in these scenarios and it even accelerates over the decades. Regarding the scenarios employing mostly nuclear and fossil generation (Big & market and Fossil & nuclear), the installation of renewable generation is relatively small, even though the amount of fossil generation decreases until 2050. Biomass, nuclear and hydro generation are almost stable in these scenarios.

2040 Grid Development

The second part of this task deals with the development of grid architectures which are able to comply with the requirements of the 2040 scenarios. These candidate grid architectures for 2040 have to be in line with the projects defined in the TYNDP for 2030 and the grid architectures for 2050 developed in e-Highway 2050. Regarding the grid model for 2030, the initial work was done in the early stage of the project and the TYNDP 2014 dataset was used. For this reason, the same “starting grid“ is used as for the 2050 analyses. In general, the same probabilistic system simulations and indicators are used for both 2040 and 2050 analyses. This allows the results to be comparable to those of the 2050 simulations.

In order to find profitable reinforcements in 2040, which are consistent with those in 2050 and common to all scenarios, a least-regret approach is chosen for the grid development. For this purpose, the 2040 grid architectures are considering all five grid architectures for 2050 by means of the average transmission capacities of all scenarios. Based on this “average 2050 grid model”, two architectures are derived and studied in detail:

- “Common grid” taking into account 50% of the average transmission capacities
- “Extended grid” taking into account 70% of the average transmission capacities

Both grid models are simulated with the data sets for 2040. Taking into consideration the investment cost, redispatch cost, energy not supplied and spillage of renewable generation, **the best grid model for 2040 is *the common grid*** (see Figure 3). However, the extended grid improves further *Large Scale RES* and *100% RES*, but is almost useless for the other scenarios.

Figure 3: Grid reinforcements proposed for 2040 in addition to the projects considered in the TYNDP 2014

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Abbreviations

CCGT	Combined cycle gas turbine
CHP	Combined heat and power
CCS	Carbon capture and storage
CSP	Concentrated solar power
DER	Distributed energy resource
DSM	Demand side management
EKC	Electricity Coordination Center; project partner in Serbia
ENS	Energy not supplied
ENTSO-E	European Network of Transmission System Operators for Electricity
LOLD	Loss of load duration
OCGT	Open cycle gas turbine
PSP	Pumped storage plant
PV	Photovoltaics
RES	Renewable energy source
RoR	Run-of-the-river
TYNDP	Ten Year Network Development Plan

Introduction

The objectives of e-Highway 2050's task 4.3 are to propose intermediate grid architectures for the Pan-European transmission grid for 2040, as well as the associated data sets for load and generation. For that purpose, task 4.3 has to derive figures for generation (installed capacity) and consumption for 2040 both at country and at cluster level, which will be used in subsequent system simulations to identify weak points and congestions in the transmission system. This step will be accompanied by the development of grid reinforcements that can help in mitigating those issues in the transmission system.

The candidate grid architectures for 2040 have to be in line with the *Ten Year Network Development Plan* (TYNDP) for 2030 developed by ENTSO-E and the grid architectures for 2050 developed in e-Highway 2050. For this purpose, task 4.3 will employ a reduced grid model for 2030 based on the current European transmission grid and the planned projects of the latest version of the TYNDP. This so called "starting grid" will be reinforced to meet the technical and economical requirements of 2040. The resulting grid architectures for 2040 will be part of the modular development plan for the Pan-European transmission grid between 2030 and 2050.

1. Description of the approach

1.1. Objectives and challenges of the work

1.1.1. <u>Scenario quantification for 2040</u>

This first step consists of the quantification of the consumption and the installed generation capacities in 2040. This work includes the determination of the annual electricity demand and the deduction of demand time series. Furthermore, figures for the installed generation capacities and the related time series for renewable generation are determined and validated by assessing the system's adequacy.

It is envisaged to use an interpolation approach from the scenarios defined in the TYNDP considering the year 2030 from ENTSO-E towards the quantified scenarios for 2050. In fact, the grid model used in work package 2 of e-Highway2050 as a starting grid was derived from the associated TYNDP grid model. Thus, the intermediate scenarios for 2040 should be consistent with both scenario assumptions for 2030 and 2050. That said, a linear interpolation approach is a good choice to compute the demand and the installed generation capacities for 2040.

The interpolation is done on country level, since this is the level on which the figures presented in the TYNDP are given. Furthermore, an assessment of the system's adequacy on country level is done before distributing the country figures for installed capacity to cluster level.

The TYNDP and e-Highway2050 are following different approaches in developing their visions/scenarios. Considering the data from both of them raises the following challenges:

- The TYNDP details 4 visions whereas e-Highway2050 describes 5 scenarios.
- The TYNDP contains 2 bottom-up and 2 top-down scenarios whereas e-Highway 2050 proposes top-down scenarios only.
- In e-Highway 2050, all grid architectures satisfy the needs of a certain scenario whereas the TYNDP defines one single grid model suitable for all of its visions.

Defining the four 2030 visions as possible origins for each 2050 scenario would introduce a new dimension of 20 possible intermediate scenarios for 2040, which would not be feasible in this context. Instead, every e-Highway 2050 scenario must either originate from one single TYNDP vision only or from a common scenario for 2030, combining the different TYNDP visions. The decision on that point should be based on an analysis of the different visions.

Possible issues on transmission level through the introduction of grid constraints will be solved by the subsequent grid development.

1.1.2. Grid development for 2040

In contrast to e-Highway2050, the TYNDP proposes only one set of transmission expansion projects suitable for all four visions in 2030. In the scenarios assuming a proliferation of renewable energies until 2050, it is very likely that the power system will face less dramatic challenges in 2040 than in 2050. For this reason, it is envisaged to group similar transmission requirements for 2040 shared by different scenarios into common models in order to find a common path for grid expansion, proposing no-regret investments between 2030 and 2050. After all, these intermediate grid architectures must be in line with the grid reinforcements considered by the project for 2050.

Along with the reduced Pan-European grid model for 2030 and the data sets for demand and generation for 2040, system simulations can be carried out for 2040 to identify weak points and congestions in the transmission system. In the subsequent grid development, the identified issues in the transmission grid are mitigated with grid reinforcements and the system simulations are repeated in order to test the impact of these reinforcements. This iterative process is repeated until all grid constraints are solved to a reasonable degree and until further reinforcements lead to a negative economic benefit.

In general, the process in task 4.3 shall be dynamic and adaptable to future versions of the TYNDP.

1.2. Available data sources

Basically two data sources are available for the work in task 4.3:

1. The TYNDP providing data for 2020 and 2030
2. The e-Highway2050 project providing data for 2050

It is envisaged to use the newest data available from ENTSO-E which is, at this time of writing, already working on the TYNDP 2016. Due to the early stage of this process, not all information is available yet. For this reason, it was decided to use the following data from the current and the upcoming TYNDP:

- Descriptions of the 2030 visions from TYNDP 2016
- Data sets for annual demand and installed generation from TYNDP 2016 for the expected progress in 2020 and for the four 2030 visions
- Assumptions based on data from TYNDP 2014
- One set of planned transmission expansion projects to be realised until 2030 from TYNDP 2014.

The following data are available from the e-Highway2050 project:

- Descriptions of the five scenarios for 2050
- Data sets for annual demand and the installed generation for each scenario
- Hourly time series for load and renewable generation for each scenario
- One reduced European grid model for 2030 called starting grid; it is based on the current transmission grid and the TYNDP 2014 projects
- Hourly time series for the grid transfer capacity (GTC) for the starting grid
- One set of transmission expansion corridors for each scenario
- Data for all transmission technologies considered to be available in 2040 and 2050
- Economic indicators used for quantifying the value of lost load (VOLL) in 2050
- Fuel and CO_2 prices for 2050

Furthermore, external data sources, such as reports and studies, were used when deemed necessary to estimate missing data.

2. Scenario Quantification for 2040

2.1. Methodology

The scenario quantification for 2040 comprises the determination of the annual demand and the installed generation capacities for each of the five e-Highway2050 scenarios by considering the 2030 visions from the TYNDP and the 2050 scenarios from the e-Highway2050 project. The quantification is done both on country and cluster level. The steps of the followed methodology are shown in Figure 4.

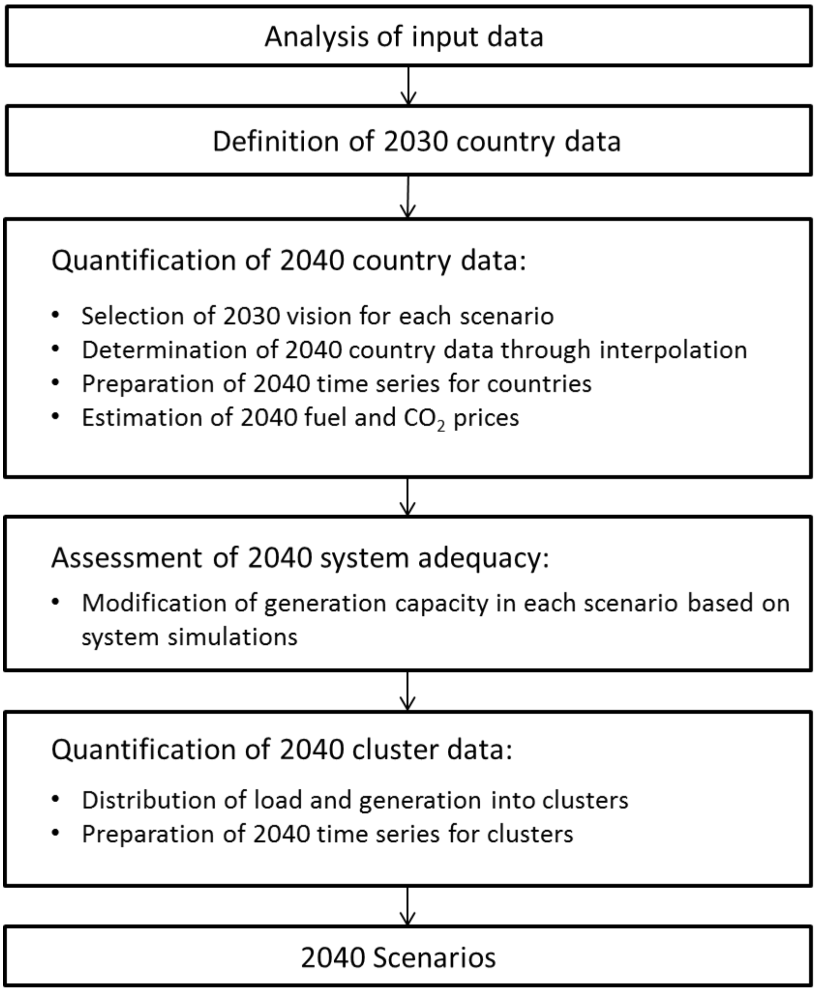


Figure 4: Flow chart for scenario quantification for 2040

Analysis of input data and definition of 2030 country data

After a detailed analysis of the TYNDP 2016 draft data, data sets for all 2030 visions are generated in line with the information provided for each 2050 scenario. This qualitative approach uses assumptions on how the information provided in the TYNDP can be mapped to the data structure used in e-Highway2050.

Quantification of 2040 country data

In a next step, an origin amongst the 2030 visions is chosen for each 2050 scenario. Since the 2030 visions and the 2050 scenarios were developed independently, both a qualitative analysis based on the description and a quantitative analysis based on concrete figures is performed. The results are used to qualify the 2040 scenarios and to highlight a possible path from 2020 to 2050 for each of them.

Once the relations between the 2030 visions and the 2050 scenarios are established, it is possible to quantify scenarios for 2030 in line with each 2050 scenario for each country. This allows enriching the 2030 data sets with scenario specific assumptions for several generation types (e.g. offshore wind in the North Sea). The 2040 scenarios are then quantified by interpolating between 2030 and 2050. This process is depicted in Figure 5. The quantification of scenarios is done on a country basis for the annual demand and the installed generation.

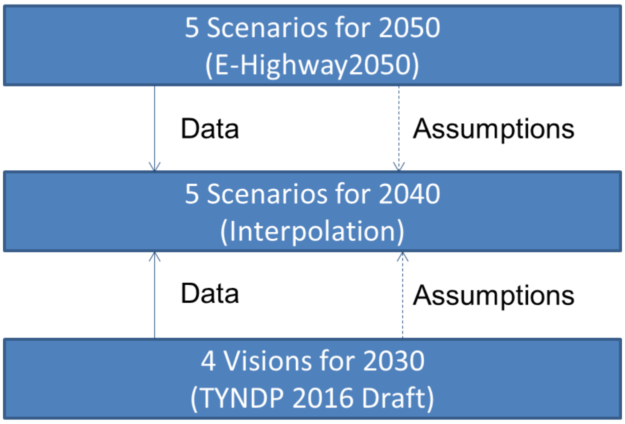


Figure 5: Determination of 2040 country data through interpolation

The simulation of flexible generation through the use of an economic dispatch requires fuel and CO_2 prices to be available for 2040. For that purpose, prices for both are estimated on the basis of several available studies and the assumptions made for 2050.

Assessment of 2040 system adequacy

After quantifying the installed generation capacities for each country, an assessment of the system adequacy with infinite transmission capacities has to take place to ensure that the demand can be covered on an European scale at all times. This process is required because only the use of limited transmission capacities will introduce constraints, which can be solved in the end by grid expansion. Thus, it must be guaranteed that the load shedding, as a last measure to keep the power system balanced in case of missing energy production, will be minimised. The indicator used for assessing the system adequacy is the *Loss of Load Duration* (LOLD) which should not exceed a certain limit per year on a European scale. An over-capacity in terms of too much flexible generation available must also be prevented in order to follow the methodology used for developing the 2050 grids and to aim for a uniform grid expansion between 2030 and 2050.

In case of missing adequacy, additional generation capacities from renewable energies, but also storage and peak units, should be added to the system. This step is similar to the approach followed in task 2.1 (see section 2.1.9 in the deliverable D2.1). In case of over-capacities in terms of available flexible generation, the latter must be reduced progressively.

Quantification of 2040 cluster data

The smallest entities in the system simulations in e-Highway2050 are *clusters* (see Figure 6) while every country is constituted by at least one cluster. The quantification of the 2040 scenarios on cluster level will be done through the application of distribution keys on the country data. This process includes the rounding of thermal generation to predefined unit sizes, which is required for the simulations. Also, the scaling of time series for demand and renewable generation is done.

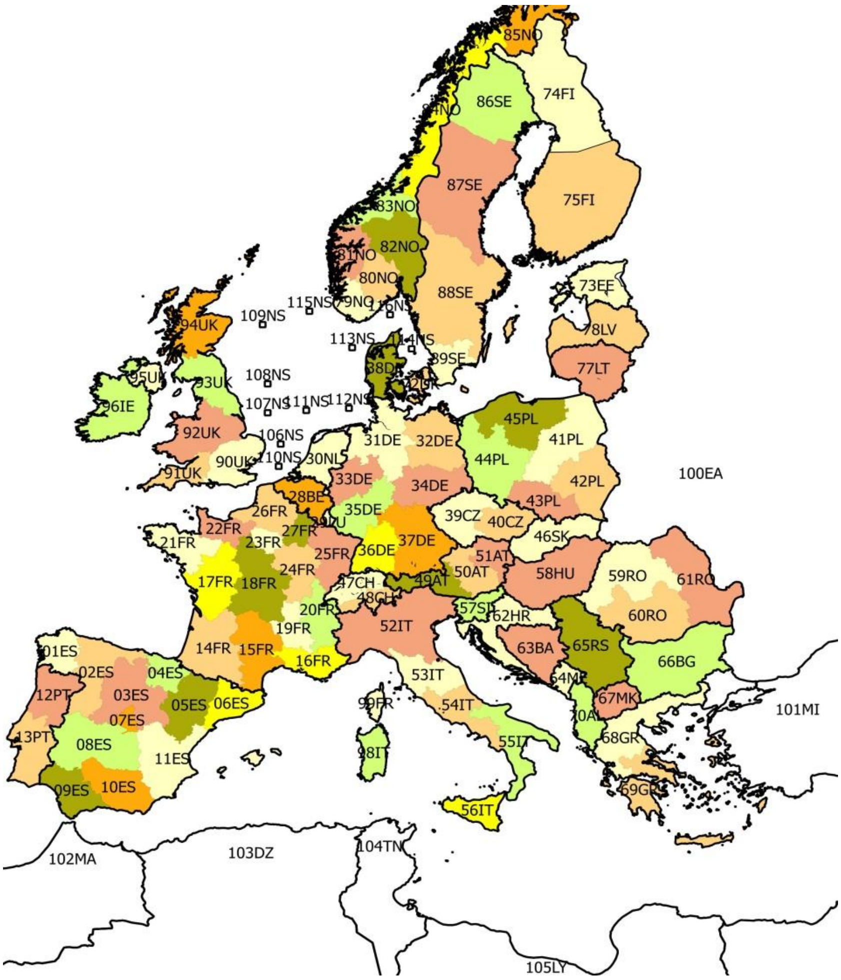


Figure 6: Map of all clusters used in e-Highway2050

2.2. Analysis of input data

An analysis of the data provided by the TYNDP is carried out. The included information is compared with the data available in the e-Highway2050 data sets. The objective is to highlight the specifics of each data provider and to identify the points where additional data and assumptions will be required. The results of this analysis are described in the following subsections.

2.2.1. Consideration of countries

The e-Highway2050 project and the TYNDP consider a slightly different list of countries. This is due to the fact that not all countries considered by e-Highway2050 are members of the ENTSO-E (e.g. Albania) or that some countries are not considered explicitly by e-Highway2050 (e.g. Cyprus, Iceland). For that reason, additional data have to be found for Albania for the year 2030.

2.2.2. Qualitative comparison of data sets

The TYNDP 2016 draft contains the following data sets:

- 1 data set for 2020 (*expected progress*)
- 4 *visions* for 2030 (V1 – V4)

Each data set contains information about:

- Annual demand (GWh)
- Installed capacity of 11 different generation technologies (MW)
- Annual generation of each generation technology (GWh)

A detailed list of the data available in the TYNDP is given in Table 9.

When comparing the data sets provided by ENTSO-E with those from e-Highway2050, the following information is available in all data sets for each country:

- Annual demand (in TWh)
- Installed generation (in MW) for:
    - gas fired power plants (aggregated value for with and without carbon capture and storage (CCS))
    - hard coal fired power plants (aggregated value for with and without CCS)
    - lignite fired power plants (aggregated value for with and without CCS)
    - nuclear power plants
    - wind (aggregated value for onshore and offshore wind)
    - solar (aggregated value for photovoltaics and concentrated solar power)
    - hydro power plants (aggregated values for run-of-the-river and pumped storage plants)

The following generation types are not included in the e-Highway2050 data sets but can be found in the TYNDP 2016:

- Other RES (aggregated value for biomass, renewable waste, tidal, wave, geothermal)
- Other non-RES (aggregated value for non-renewable CHP, waste and other not clearly defined generation)
- Biofuels fired power plants
- Oil fired power plants

The following types of generation are handled explicitly in e-Highway2050 and the TYNDP does not contain specific information about:

- Offshore wind situated in the North Sea
- Photovoltaics and concentrated solar power situated in North Africa
- Different types of hydro generation (run-of-the-river without reservoir, run-of-the-river with reservoir, pumped storage plants)
- Explicit figures for photovoltaics and concentrated solar power
- Peaking units in terms of gas fired power plants (OCGT technology) or other technologies (e.g. storages, demand side management), depending on the scenario

All information about generation capacities, which are not directly available in the TYNDP, must be provided through additional data from other sources and/or through adequate assumptions.

2.2.3. Consideration of generation flexibility

E-Highway2050 considers generation from biomass to be dispatchable (i.e. flexible) and biomass units to compete on the regular electricity market. In the TYNDP instead, biomass (as part of the generation type “Other RES”) is considered to be non-dispatchable (i.e. inflexible). This might have an influence in simulations with scenarios dominated by renewable energies, where biomass could be one of the few providers of dispatchable generation and thus of flexibility for the power system.

In general, due to the different consideration of generation flexibility, the mapping of the generation types “Other RES”, “Other non-RES” and “Oil” from the TYNDP to the data structure used in e-Highway2050 might have an impact on the amount of dispatchable generation units in the simulations.

2.2.4. Methodology for assessing the system adequacy

The methodologies for assessing the system adequacy used in e-Highway2050 and in the development of the TYNDP are not exactly the same. A difference consists in the consideration of transmission capacities in both studies. While e-Highway2050 neglects all grid constraints for this specific kind of assessment, a grid model with limited transmission capacities was considered for the assessment during the work on the TYNDP. For this reason, copperplate simulations in e-Highway2050 might need less flexible generation to comply with the system adequacy in 2040 than foreseen by the TYNDP in 2030.

2.3. Definition of 2030 country data

2.3.1. Assumptions for Albania

Since Albania is not a part of ENTSO-E, data is not provided in the TYNDP. Thus, the total annual demand is assessed on the basis of in-house data from EKC. In 2012, the annual demand amounted to 7700 GWh. Assuming an average rate of 1.7% until 2030, the demand in 2030 is assessed as 10500 GWh.

Regarding the installed generation capacities, there are no known official publicly available data for Albania in 2030. For this reason, an interpolation approach is used, starting with today's values and interpolating until 2050 in different scenarios. Based on the latest published data by the Albanian energy regulator ERE [1] and internal data from EKC, the following installed generation is foreseen in 2015:

- 1475 MW in hydro power plants with storages
- 120 MW in run-of-the-river plants
- 98 MW in combined-cycle plant using oil and gas
- 0 MW wind and 0 MW solar

2.3.2. Relation between data from TYNDP and e-Highway2050

Based on the analysis of the TYNDP data, one-to-one relationships between the information in the data sets from TYNDP and e-Highway2050 are defined in Table 1.

With only the exception of Great Britain, all fossil generation is declared to not use carbon capture and storage (CCS) in 2030. Only a certain amount of gas fired power plants is using CCS in Great Britain in two out of four visions.

Table 1: Mappings from TYNDP data to e-Highway2050 data

TYNDP data type per country	e-Highway2050 data type per country
Annual demand [TWh]	Annual demand [TWh]
Gas [MW]	Gas without CCS [MW]
Hard coal [MW]	Hard coal without CCS [MW]
Oil [MW]	
Lignite [MW]	Lignite without CCS [MW]
Nuclear [MW]	Nuclear [MW]
Wind [MW]	Total wind [MW] (onshore and North Sea)
Solar [MW]	Total solar [MW] (photovoltaics and concentrated solar power)
Hydro [MW]	Total hydro [MW] (run-of-the-river, with reservoir,

	pumped hydro storage)
Biofuels [MW]	Total Biomass [MW]
Other RES [MW]	
Other non-RES [MW]	Fossil generation [MW] (internal type used for reducing generation; see section 0)

The data prefixed with "total" are input to more specific generation types used in e-Highway2050 as shown in Table 2.

Table 2: Aggregated and detailed generation types in e-Highway2050

Aggregated generation type	Detailed generation types
Total wind	• Onshore and offshore wind outside the North Sea • Offshore wind situated in the North Sea
Total solar	• Photovoltaics • Concentrated solar power
Total hydro	• Run-of-the-river without reservoir • Run-of-the-river with reservoir (+capacity) • Pumped storage plant (+reservoir capacity)
Total biomass	• Biomass 1 (cheap biomass) • Biomass 2 (expensive biomass)

2.3.3. Assumptions for hydro power

The e-Highway2050 data sets describe three different types of hydro generation:

- Run-of-the-river without reservoir
- Run-of-the-river with reservoir
- Pumped storage plant (PSP)

Whereas the run-of-the-river (RoR) generation can be considered to be renewable and PSP to be non-renewable, a first separation can be made by using the ratio between renewable and non-renewable hydro generation. Unfortunately, the TYNDP 2016 draft does not contain more information about hydro generation than the total installed capacity and the annual energy produced. For this reason, this ratio was computed with the figures from the TYNDP 2014 for each country and applied to the aggregated value for hydro from the TYNDP 2016 draft.

Furthermore, it is assumed that the share in 2040 between RoR with and without reservoir is the same as in 2050, for which the concrete figures are available. Using the ratio between the two RoR types in 2050, both types can be calculated with the information about renewable hydro generation in 2040.

Finally, proportionality of the installed generation capacity and the size of reservoirs between 2030 and 2050 is assumed. The application of the 2050 ratios for each country to the 2030 values for installed generation of hydro with reservoir and PSP allowed computing the size of the reservoirs.

The same patterns for natural inflows were assumed for all RoR generation in 2040 and 2050. Thus, the related time series were scaled proportionally to the installed capacities in both decades.

2.3.4. Assumptions for biomass

Two types of biomass units are considered in e-Highway2050, only differing in the fuel prices. Since the use of each type is scenario-dependant, proportionality of both types between 2030 and 2050 is assumed. The ratio between both types in 2050 is used to compute the installed capacity for each country in 2030.

2.3.5. Assumptions for the North Sea

The e-Highway2050 data sets contain information about onshore and offshore wind generation, the latter only situates in the North Sea. Since the TYNDP does not contain data about offshore generation specifically in the North Sea, the offshore wind capacities in the North Sea are distributed. For this purpose, additional data was provided by ENTSO-E for onshore and offshore wind generation, based on preliminary data from TYNDP 2016. Table 3 contains the distribution of the installed offshore wind power in North Europe among the different offshore regions.

Table 3: distribution keys for offshore wind

	North Sea	Baltic Sea	Irish Sea
Germany	75%	25%	0%
Denmark	50%	50%	0%
Sweden	25%	75%	0%
UK	75%	0%	25%

Only three regions are considered: North Sea, Baltic Sea and Irish Sea. The Atlantic Ocean is omitted, because there are little concrete offshore wind deployment plans at the moment. This is mainly due to the water depth, which is significantly deeper than the three considered regions. Floating wind turbines could be installed there in the future, but as this development is uncertain at the moment, it is difficult to consider it properly.

The shares between the three regions have been estimated roughly, based on the location and installed power of wind power plants in operation, under construction, under development or under consideration.

2.3.6. Assumptions for North Africa

Seeing the huge differences in the forecasted installed generation in North Africa and the uncertainties in the development of the Desertec project, the following approach is used for getting figures for 2030: it is assumed that no generation specifically dedicated to be exported to Europe will be built before 2020. Thus, a zero generation in 2020 will be used as a starting point for an interpolation towards 2050. This way, the uncertainties about Desertec are already included in the scenario assumptions for 2050 and no additional assumptions about Desertec have to be made for 2030 or 2040.

2.3.7. Assumptions for concentrated solar power

Prognoses for the deployment of concentrated solar power (CSP) in Europe see the highest potential in South Europe and mainly in Spain, where actually 2.3 GW of installed generation already exist [4]. However, the forecasted generation in 2030 and 2040 differs at a high degree ([2] - [5]). For this reason, the ratio between PV and CSP in 2050 is used to compute the installed capacity of CSP for each country in 2030 by considering the aggregated value for solar power. This way, the uncertainties about the development of CSP are already included in the scenario assumptions for 2050 and no additional assumptions have to be made for 2030 or 2040.

2.4. Quantification of 2040 country data

2.4.1. Selection of 2030 vision for each scenario

In a first step, the differences between the installed generation in the 2030 visions with regards to the 2050 scenarios are studied. It turned out that a common scenario for 2030 in line with the TYNDP visions is not reasonable, due to the high discrepancies in installed generation on country level. For this reason, this approach is rejected and four different scenarios for 2030 in line with the TYNDP visions are defined instead. As a consequence, the philosophies of the 2030 visions and the 2050 scenarios can be aligned to highlight a possible roadmap from today until 2050.

For each 2050 scenario, one possible origin in 2030 amongst the TYNDP visions is identified. For this purpose, a qualitative and quantitative analysis is carried out in order to select the most logical evolution in demand and generation from 2020 to 2050 in each scenario. All generation technologies and the annual demand are considered in this process. The chosen combinations of 2030 visions and 2050 scenarios are displayed in Figure 7.

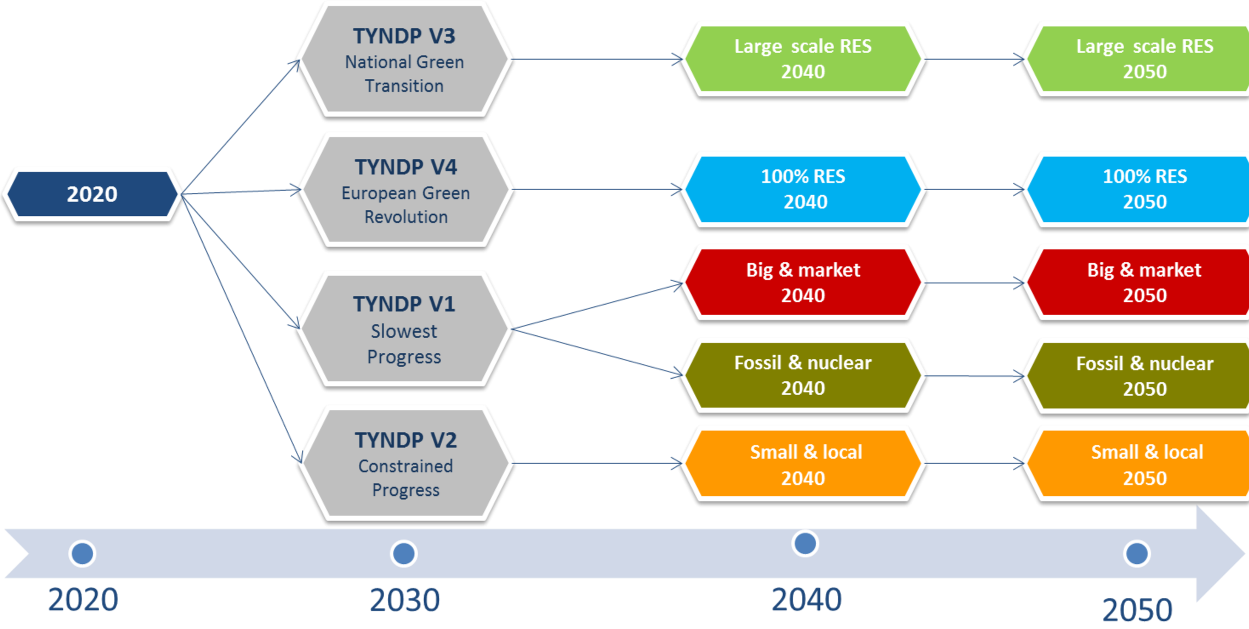


Figure 7: 2040 Scenarios - from today to 2050

This process was supported by a dedicated Excel macro allowing for visualising the trend of all generation technologies and the annual demand for all combinations of 2030 visions and 2050 scenarios.

2.4.2. Determination of 2040 country data through interpolation

An interpolation approach is chosen for determining the annual demand and the installed generation in 2040. A linear interpolation between the years 2030 and 2050 seems to be the most logic evolution, when considering all data at once in two different data sets.

The actual interpolation was implemented in Excel.

2.4.3. Rounding of thermal generation units

The computed raw values for installed generation in 2040 in each country must be rounded to a type specific unit size in order to be used in simulations. The resulting values are the number of generating units bound to a specific unit size. However, the linear interpolation between two different data sets might produce strange results on country level in terms of illogical or even forbidden evolutions. To circumvent this drawback, the following criteria are adopted, while adapting the computed number of units:

- National regulations shall be respected when considering the opt-out of technologies in certain countries (nuclear phase-out of Germany in 2022, Belgium in 2025 and Switzerland in 2034).
- The difference between the raw European value and the sum of all units in all countries should be smaller than half of the unit size.

A dedicated Excel macro was developed to analyse the effect of rounding to unit size on the installed capacity of all thermal generating units. Furthermore, it allows for adapting the automatically chosen unit numbers to comply with the aforementioned criteria and to write the resulting installed capacity into an output Excel file.

2.4.4. Scaling of time series

Based on the annual demand in 2040 and 2050, the demand time series for 2050 for every country, including demand side management, are scaled to meet the annual demand in 2040 in each country. This work is done through a dedicated Excel sheet.

2.4.5. Estimation of fuel and CO_2 prices for 2040

Based on the assumptions for 2050, the general scenario descriptions and external sources ([6], [7] and [8]), fuel prices are estimated for all thermal generation technologies. The CO2 price was estimated to 189€/tonne. The final marked bids are shown in Table 4.

Table 4: Market bids used in system simulations for 2040 (prices in €/MWh)

Generation Technology	Large scale RES	100% RES	Big & market	Fossil & nuclear	Small & local
OCGT	157	168	160	160	168
CCGT without CCS	110	117	88	88	117
CCGT with CCS	68	78	40	40	78
Coal without CCS	139	144	139	139	144
Coal with CCS	41	47	41	41	47
Lignite without CCS	156	156	156	156	156
Lignite with CCS	25	25	25	25	25
Nuclear	14	20	14	14	14
Biomass1	20	10	20	20	10
Biomass2	135	20	135	135	20

2.5. Assessment of 2040 system adequacy

2.5.1. Process description

The assessment of the system adequacy of the 2040 scenarios is done through system simulations using Antares which consider infinite transmission capacities (the so called "copperplate" simulations). The adequacy indicator used for assessing the system's adequacy is the loss of load duration (LOLD), representing the length of shortfalls (load shedding).

2.5.1. Results for 2040 scenarios

These copperplate simulations using the 2040 data show that the load could be served in all hours in all scenarios in 2040. Thus, the LOLD is zero in all cases. This situation is in direct contrast to the observations made while developing the 2050 scenarios, where additional generating units had to be added until the LOLD falls below a defined threshold (smaller than 3 hours on an European level in average over all 99 combinations of time series). For this reason, the development process employed for 2040 is trying to reach the same level of adequacy in order to aim for a uniform grid expansion between 2030 and 2050. In this context, a missing LOLD means that the power system has a too high flexibility in terms of dispatchable generation. Therefore the generation of flexible power plants must be reduced. This is done in an iterative, automatic process which is similar to the one followed during the quantification of the 2050 scenarios. The basic idea is to reduce the installed generation of gas fired power plants step by step and to check the system adequacy after each step through system simulations. In each step, the installed generation is reduced by 5%. This process is repeated until a minimal LOLD is reached on a European level.

2.5.2. Reduction of generation capacity in 2040 scenarios

The aforementioned methodology is applied to the 2040 scenarios. It is observed that the generation to be reduced in 2040 amounts the order of magnitude of a specific generation type in 2040, which was interpolated originally from the type "Other non-RES" in 2030. This observation is true for all five scenarios. For this purpose, this specific generation type is removed from the 2040 data sets and the system adequacy is assessed again by means of copperplate simulations. The results show that a small LOLD is reached in three out of five scenarios. This phenomenon is observed in the scenarios "100% RES", "big & market" and "fossil & nuclear".

A further reduction of the generation by 25% is required for the scenarios "large scale RES" and "small & local".

2.6. Quantification of 2040 cluster data

2.6.1. Distribution of load and generation to clusters

The installed generation and the annual demand in each cluster are derived from country values by using distribution keys developed for 2050 (see deliverable D2.1). The calculation of cluster values for each country and each scenario is done with dedicated Excel sheets.

2.6.2. Rounding of thermal generation units

This process is identical to the one described in section 2.4.3, with only the exception of an additional criterion:

- The difference between the raw country value and the sum of all units in all clusters in this country should be smaller than half of the unit size.

2.6.3. Scaling of time series

Based on the annual demand in 2040 and 2050, the demand time series for 2050 for every cluster were scaled to meet the annual demand in 2040 in each cluster. This work was done through a dedicated python script.

2.7. Results of Scenario Quantification – 2040 scenarios

2.7.1. Scenario X-5 – Large Scale RES

General description

The scenario "Large scale RES" is the scenario with the highest demand of all scenarios in 2040, accounting for 4300 TWh per year. This is due to a low increase of energy efficiency (including demand side management and flexibility of EV use) together with a high level of new uses of electricity (electrification of transport, heating and industry). Based on the general scenario description, fuel costs are relatively low and CO_2 costs are high.

This scenario focuses on the deployment of large scale RES technologies only, especially through large offshore wind parks in the North Sea and high imports from North Africa. Also nuclear generation is considered but remains nearly at the level of 2020. Only a small amount of decentralised RES is assumed by means of biomass and combined heat and power generation.

The final installed generation capacities are shown in Figure 8.

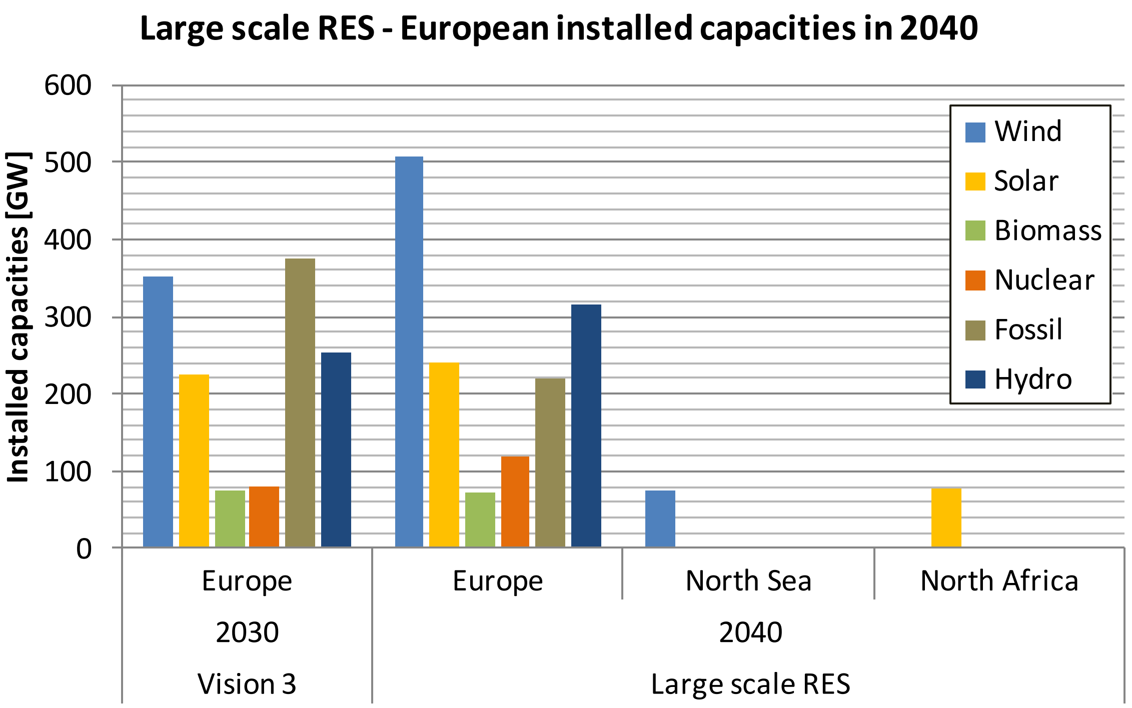


Figure 8: European installed capacities in scenario "Large scale RES" in 2040

Quantification performance

System simulations with the quantified installed generation and demand show the energy mix depicted in Figure 9.

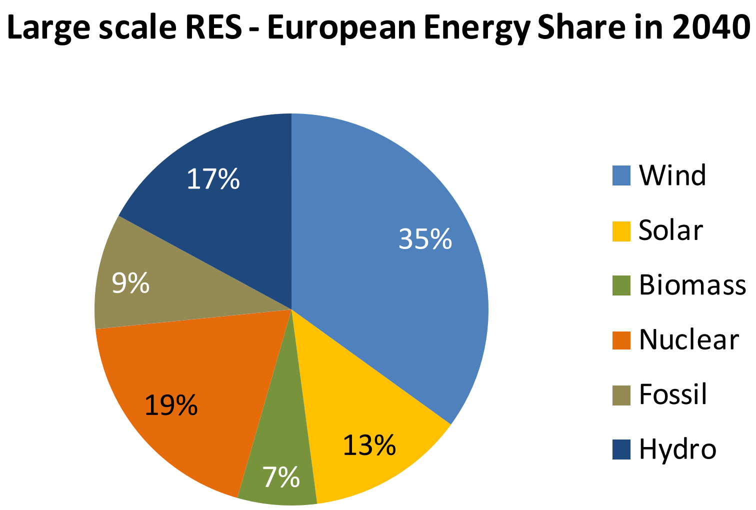


Figure 9: European energy mix in scenario "Large scale RES" in 2040 (including imports from North Africa)

The main conclusions at European level are:

- 72% of the produced energy is provided by renewable energy sources (wind, solar, biomass and hydro generation)

- 48% of the energy produced in Europe is provided by wind and solar generation only
- 20% of the wind energy is produced in the North Sea
- 43% of the solar energy is produced in North Africa
- Wind generation in the North Sea covers 7% of the annual demand
- Solar generation in North Africa covers 6% of the annual demand

2.7.2. Scenario X-7 – 100% RES

General description

The scenario “100% RES” has the highest ambition for the year 2050: it targets to base the European energy supply entirely on renewable energies. Regarding the demand in this scenario, it will reach a moderate level of 4000 TWh per year in 2040 despite a high level of new uses of electricity (electrification of transport, heating and industry). This is due to a higher increase of energy efficiency (including demand side management and flexibility of EV use). Based on the general scenario description, both fuel and CO_2 costs are high.

This scenario focuses on the deployment of both large scale RES technologies, especially through large offshore wind parks in the North Sea and high imports from North Africa, but also on small scale solutions like decentralised RES by means of biomass and combined heat and power generation. Capacities for nuclear generation are considered to decrease to one third compared to the level of 2020.

The final installed generation capacities are shown in Figure 10.

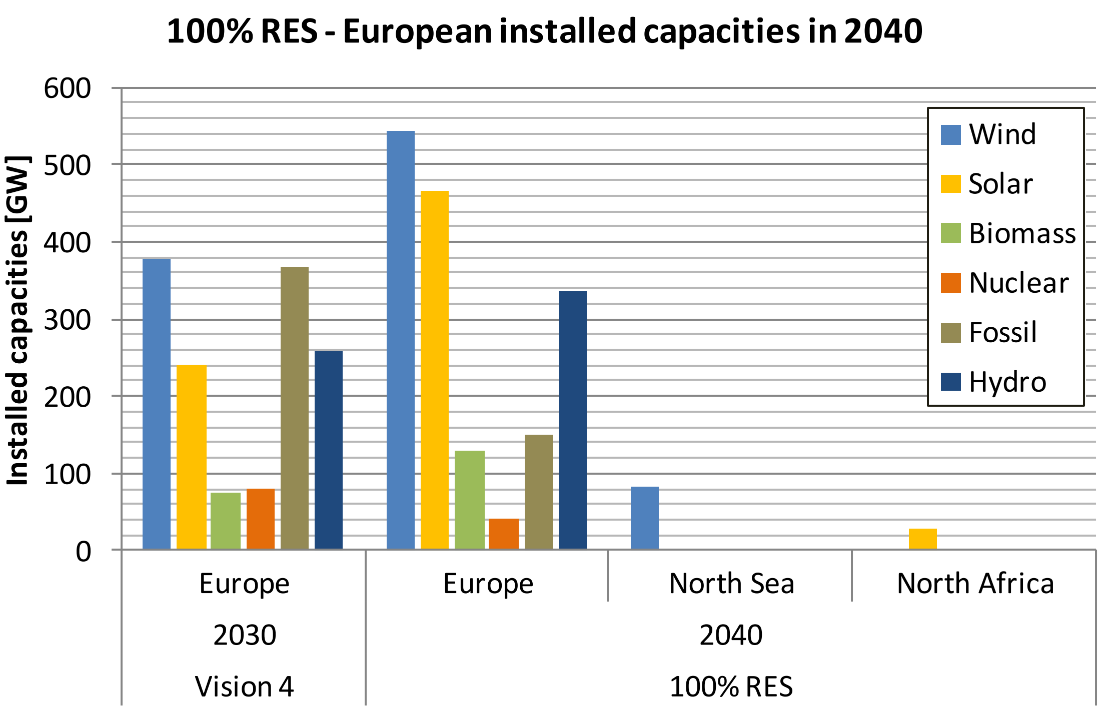


Figure 10: European installed capacities in scenario “100% RES” in 2040

Quantification performance

System simulations with the quantified installed generation and demand show the energy mix depicted in Figure 11.

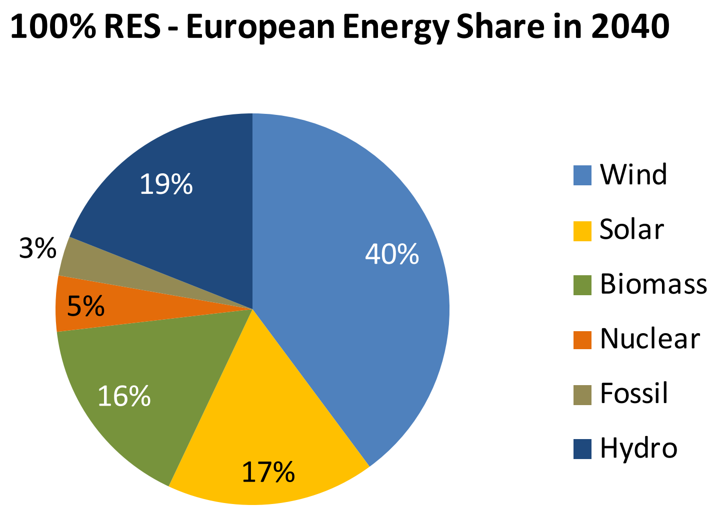


Figure 11: European energy mix in scenario "100% RES" in 2040 (including imports from North Africa)

The main conclusions at European level are:

- 92% of the produced energy is provided by renewable energy sources (wind, solar, biomass and hydro generation)
- 57% of the energy produced in Europe is provided by wind and solar generation only
- 20% of the wind energy is produced in the North Sea
- 12% of the solar energy is produced in North Africa
- Wind generation in the North Sea covers 8% of the annual demand
- Solar generation in North Africa covers 2% of the annual demand

2.7.3. Scenario X-10 – Big and Market

General description

The scenario "big and market" has a rather low demand in 2040 (around 3900TWh) which is mainly due to a low level of new uses of electricity (electrification of transport, heating and industry) together with a low increase of energy efficiency (including demand side management and flexibility of EV use). Based on the general scenario description, the fuel costs are low and CO_2 costs are high.

This scenario focuses mainly on the deployment of large scale RES technologies, mainly through large offshore wind parks in the North. Only few solar generation capacities designated for exports to Europe are considered in North Africa. Another emphasis is given to nuclear technology and fossil fuel plants using CCS technology.

The final installed generation capacities are shown in Figure 12.

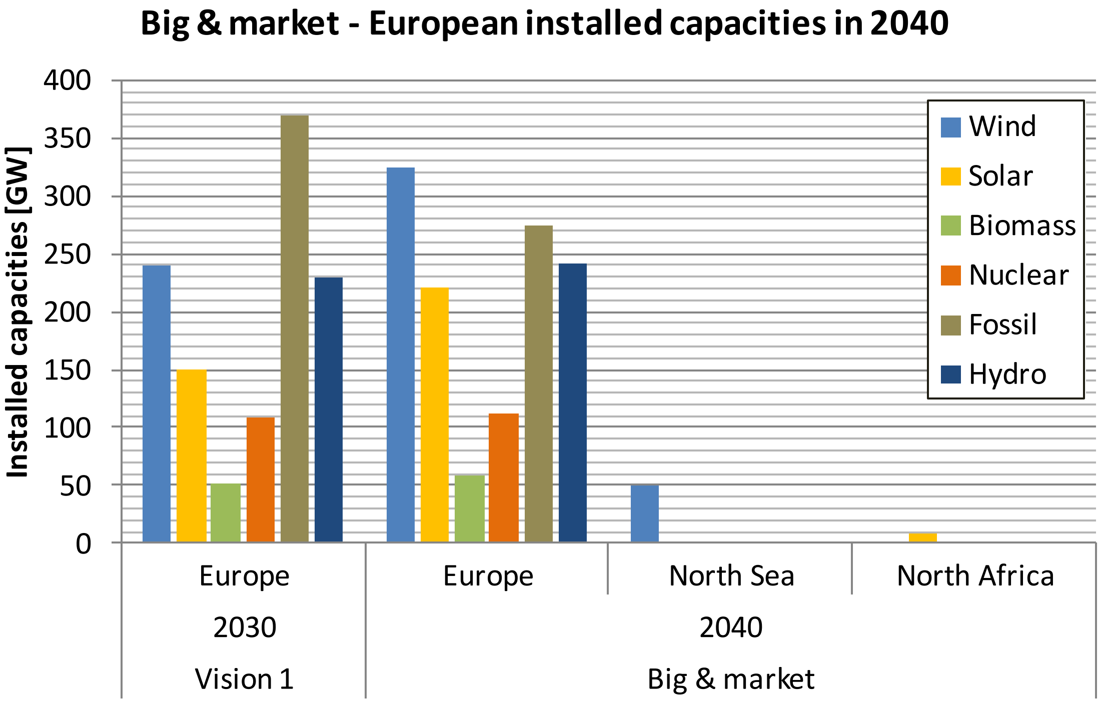


Figure 12: European installed capacities in scenario “big and market” in 2040

Quantification performance

System simulations with the quantified installed generation and demand show the energy mix depicted in Figure 13.

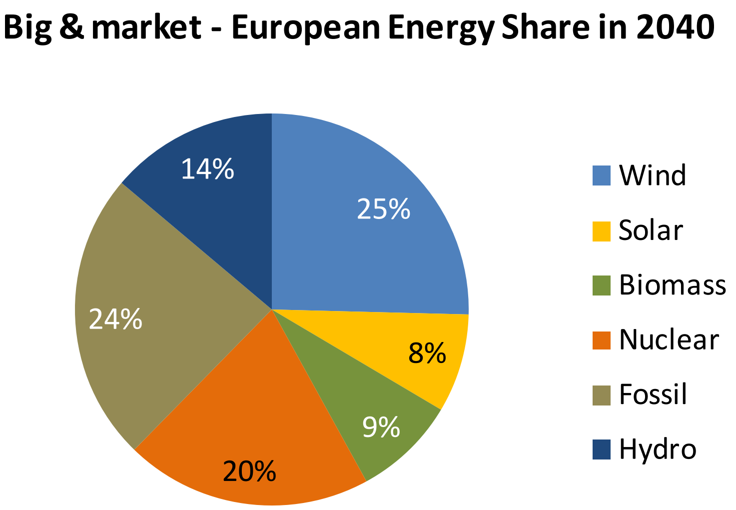


Figure 13: European energy mix in scenario "big and market" in 2040 (including imports from North Africa)

The main conclusions at European level are:

- 56% of the produced energy is provided by renewable energy sources (wind, solar, biomass and hydro generation)

- 33% of the energy produced in Europe is provided by wind and solar generation only
- 20% of the wind energy is produced in the North Sea
- 9% of the solar energy is produced in North Africa
- Wind generation in the North Sea covers 5% of the annual demand
- Solar generation in North Africa covers 1% of the annual demand

2.7.4. Scenario X-13 – Fossil and Nuclear

General description

The scenario "fossil and nuclear" has a rather high demand in 2040 (4100TWh) which is mainly due to a moderate level of new uses of electricity (electrification of transport, heating and industry) together with a moderate increase of energy efficiency (including demand side management and flexibility of EV use). Based on the general scenario description, the fuel costs are low and CO_2 costs are high.

This scenario focuses mainly on the deployment of non-renewable large scale generation as e.g. nuclear and fossil fuel plants with CCS. Only smaller generation capacities are considered in the North Sea while no energy imports from North Africa are foreseen. The final installed generation capacities are shown in Figure 14.

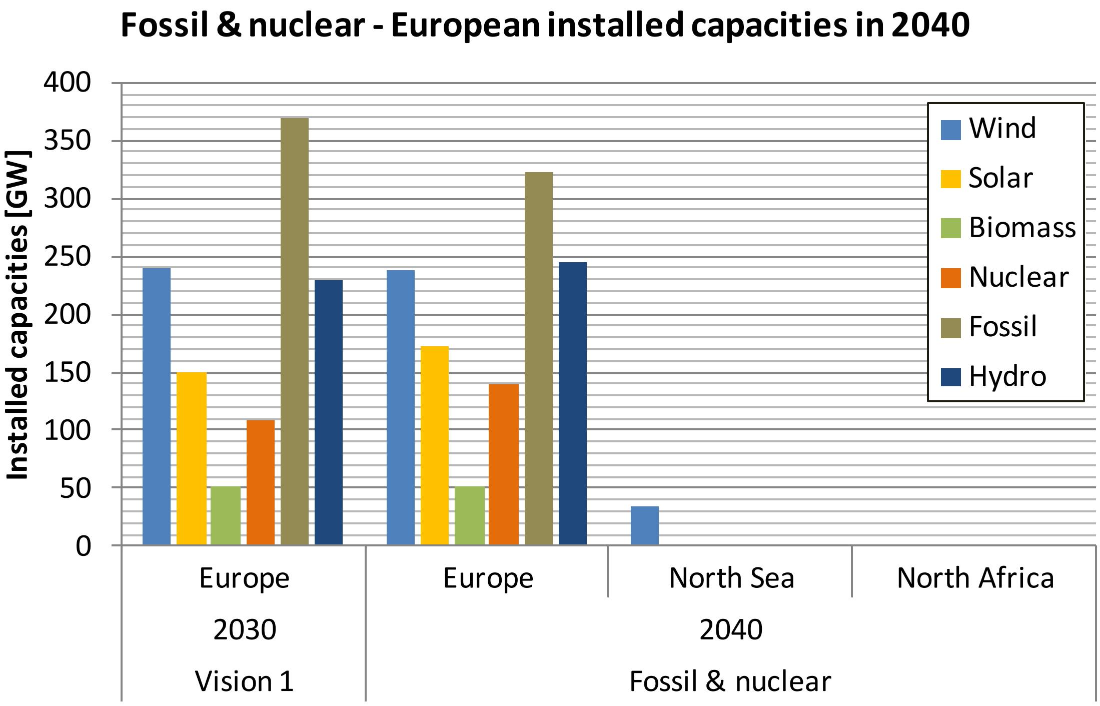


Figure 14: European installed capacities in scenario "fossil and nuclear" in 2040

Quantification performance

System simulations with the quantified installed generation and demand show the energy mix depicted in Figure 15.

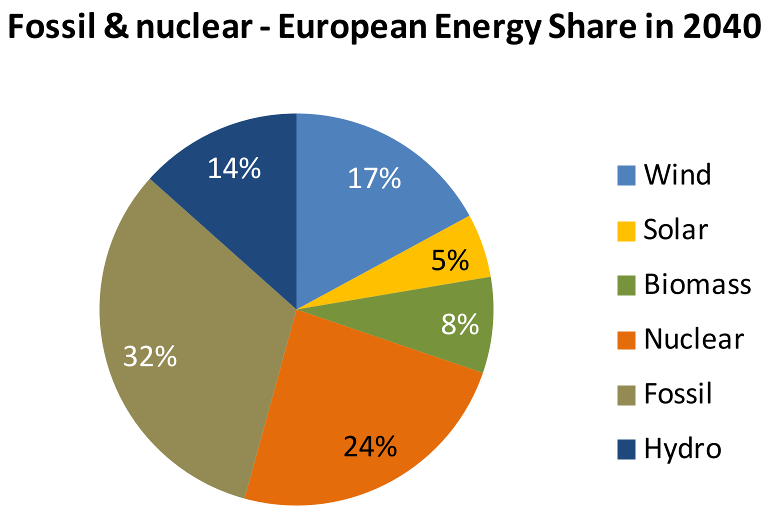


Figure 15: European energy mix in scenario "fossil and nuclear" in 2040 (including imports from North Africa)

The main conclusions at European level are:

- 44% of the produced energy is provided by renewable energy sources (wind, solar, biomass and hydro generation)
- 22% of the energy produced in Europe is provided by wind and solar generation only
- 19% of the wind energy is produced in the North Sea
- no solar energy is imported from North Africa
- Wind generation in the North Sea covers 3% of the annual demand

2.7.5. Scenario X-16 – Small and Local

General description

The scenario “small and local” is the scenario with the lowest demand of all scenarios in 2040, accounting for 3270 TWh per year which is even smaller than foreseen in 2020. This is due to a high increase of energy efficiency (including demand side management and flexibility of EV use) together with a low level of new uses of electricity (electrification of transport, heating and industry). Based on the general scenario description, both fuel and CO_2 costs are high.

This scenario focuses on the deployment of mainly small scale and local solutions for both RES and storage. Thus decentralised generation, storage and smart grid solutions, especially on distribution level, are favoured over nuclear and fossil fuel plants with CCS.

Thus, only a smaller deployment of offshore wind parks in the North Sea and smaller energy imports from North Africa are foreseen. Instead decentralised RES, like e.g. biomass and combined heat and power generation, are considered. The final installed generation capacities are shown in Figure 16.

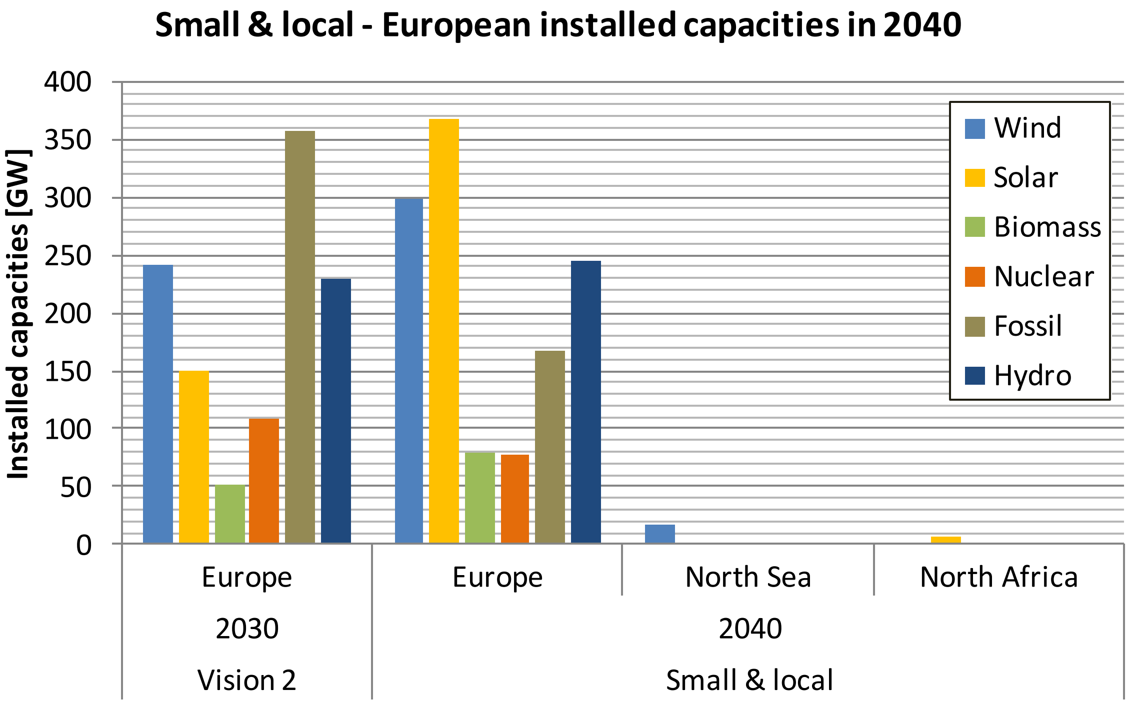


Figure 16: European installed capacities in scenario "small and local" in 2040

Quantification performance

System simulations with the quantified installed generation and demand show the energy mix depicted in Figure 17.

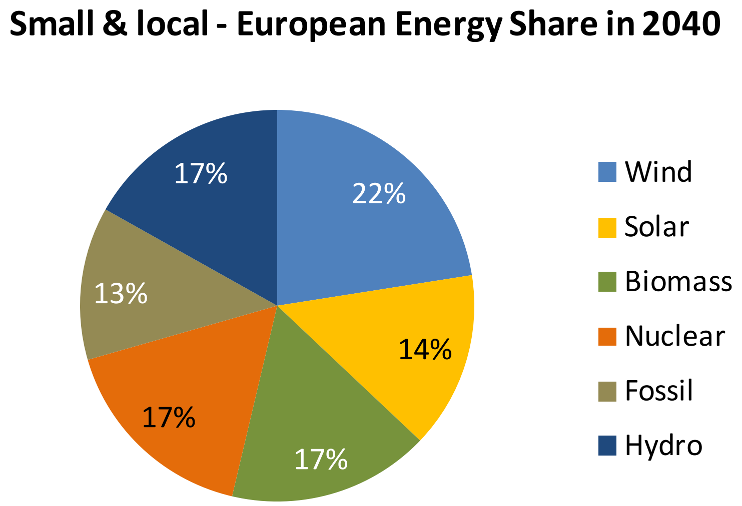


Figure 17: European energy mix in scenario "small and local" in 2040 (including imports from North Africa)

The main conclusions at European level are:

- 70% of the produced energy is provided by renewable energy sources (wind, solar, biomass and hydro generation)
- 36% of the energy produced in Europe is provided by wind and solar generation only
- 9% of the wind energy is produced in the North Sea
- 4% of the solar energy is produced in North Africa
- Wind generation in the North Sea covers 2% of the annual demand
- Solar generation in North Africa covers 0.6% of the annual demand

2.7.6. Comparison of all scenarios

The annual demand in all scenarios together with the reference value for 2020 is depicted in Figure 18.

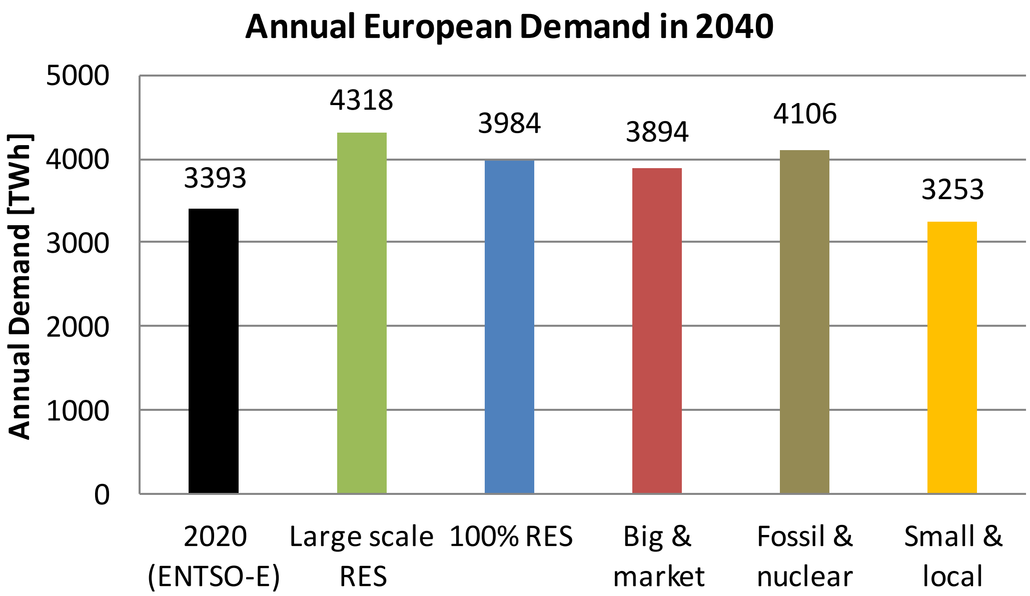


Figure 18: Annual European demand in all scenarios in 2040

The energy mix in all scenarios in 2040 is shown in Figure 19.

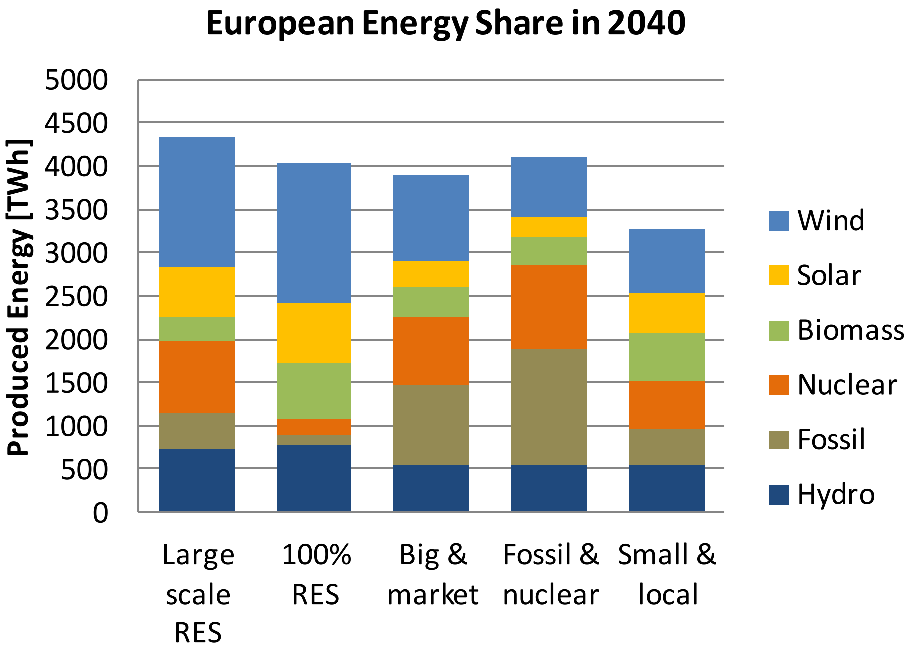


Figure 19: European energy mix in all scenarios in 2040 (including imports from North Africa)

The installed generation capacities in all scenarios are shown in Figure 20.

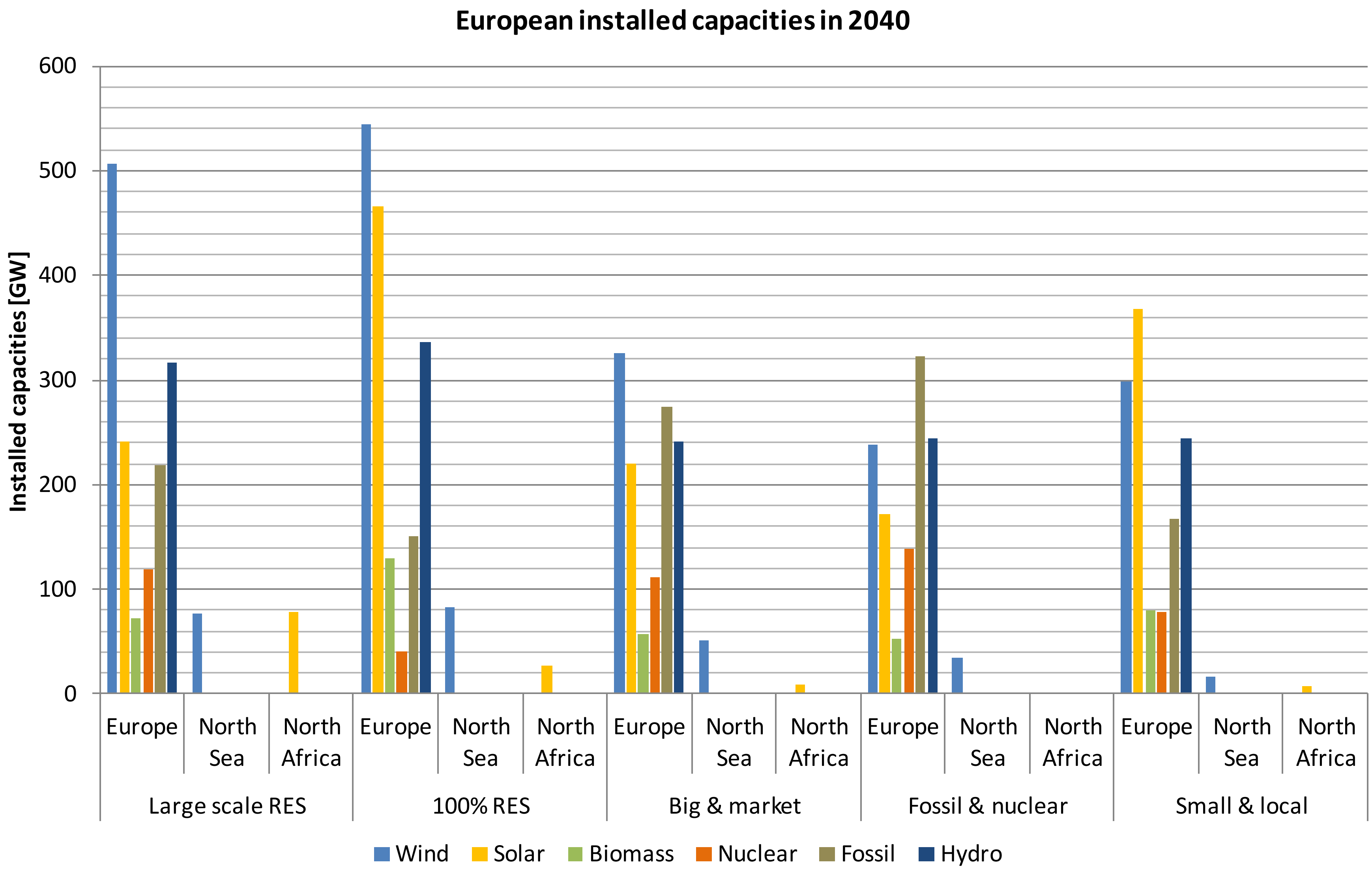


Figure 20: European installed capacities in all scenarios in 2040

3. Grid Development for 2040

3.1. Methodology

The grid development for 2040 foresees the identification of grid constraints in the transmission system and the development of appropriate grid reinforcements which are able to satisfy the transmission requirements in all scenarios. The steps followed by the methodology are shown in Figure 21.

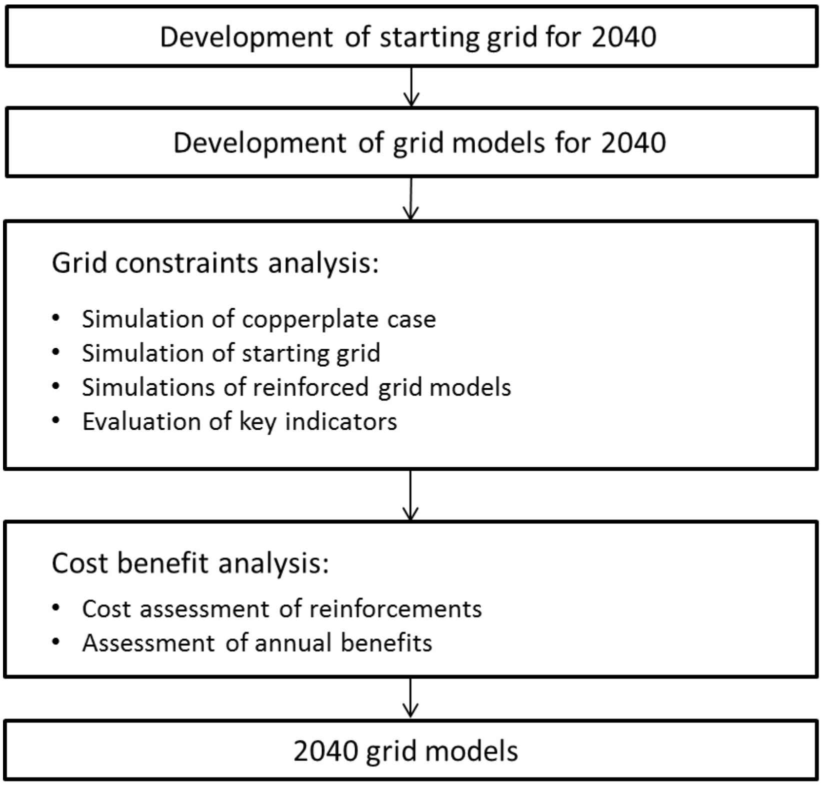


Figure 21: Flow chart for grid development for 2040

Development of starting grid for 2040

Based on the reduced grid model for 2030 of the Pan-European transmission system, a grid model has to be developed whose constraints will be analysed for all scenarios in the subsequent steps. The differences to the grid model for 2030 concern the connections to the North Sea, North Africa, the Middle East, and Eastern Europe.

Development of grid models for 2040

The grid reinforcements to be proposed for 2040 have to be in line with the reinforcements foreseen for 2050. For this purpose, neither new transmission requirements, nor new corridors will be proposed. Instead, a common path for transmission grid expansion between 2030 and 2050 has to be found, considering least-regret investments for the manifold 2050 scenarios. This is done by identifying transmission requirements shared by most scenarios.

Grid constraints analysis

The grid constraints in 2040 are identified by simulations of the non-reinforced starting grid with the data sets for 2040. The considered reinforcements are then tested through further simulations and the results are analysed by means of the following indicators: energy not supplied, loss of load duration, redispatch, spillage and operational costs. Their values in the reinforced grids are compared with those from the copperplate and the starting grid simulations, which define respectively the best case (no grid constraints) and the worst case (maximal grid constraints). The comparison gives an estimation of the quality of the grid.

Cost benefit analysis

An assessment of the costs and benefits of the proposed grid reinforcements is done for all scenarios. By considering specific technologies for all reinforcements, it is possible to estimate investment costs and their annuities. Through the comparison of the annual costs with the benefits for the overall power system, an economic selection of the most advantageous grid model is then done.

In order to facilitate the comparison with the 2050 investments, the same costs of technologies are assumed for 2040 than for 2050. The investment costs were taken from D3.1.

3.2. Development of starting grid for 2040

3.2.1. Reduced European Grid Model

The grid development is based on the analysis of the constraints in the starting grid, which was obtained by reduction of the European transmission network for 2030. The resulting grid is shown in Figure 22. The exact procedure to obtain the grid is described in the e-Highway2050 deliverable D2.2.

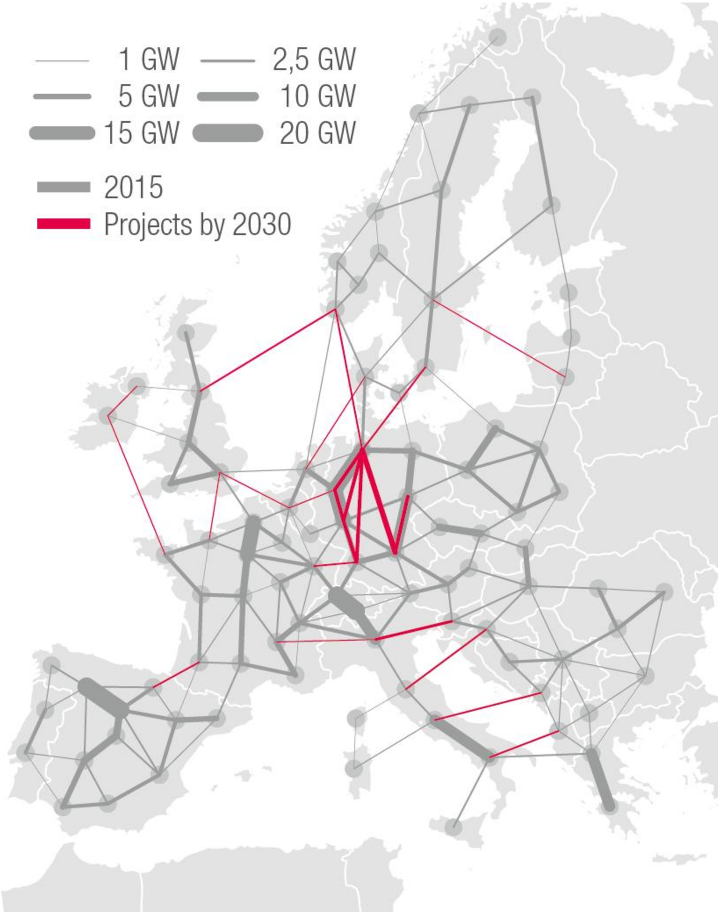


Figure 22: Reduced Grid Model for 2030

3.2.2. Connections with offshore clusters in the North Sea

The North Sea connections are handled scenario-wise since their transmission capacity is considered to be relative to the installed wind generation in each North Sea cluster. In general, the North Sea grid, and more specifically the meshed offshore grid, was not studied in depth in task 4.3.

Table 5 lists the transmission capacities for each scenario and Figure 23 shows the location of the North Sea clusters together with their connections to the corresponding onshore clusters.

Table 5: Links to the North Sea clusters

	Transmission capacity [MW]				
Link	Large Scale RES	100% RES	Big & Market	Fossil & Nuclear	Small & Local
106_ns - 90_uk	13 600	15 800	9 900	8 500	3 100
107_ns - 92_uk	6 800	9 800	5 200	3 200	2 400

108_ns - 93_uk	1 600	700	500	1 000	200
109_ns - 94_uk	1 600	2 100	500	1 000	200
110_ns - 28_be	3 500	7 800	6 500	6 900	1 800
111_ns - 30_nl	5 100	6 600	4 900	3 200	400
112_ns - 31_de	16 000	11 100	10 100	7 900	6 400
113_ns - 38_dk	9 800	4 800	5 200	1 800	2 000
114_ns - 72_dk	3 400	1 900	1 400	1 100	300
115_ns - 79_no	200	3 800	200	0	0
116_ns - 88_se	1 000	1 000	200	1 100	100

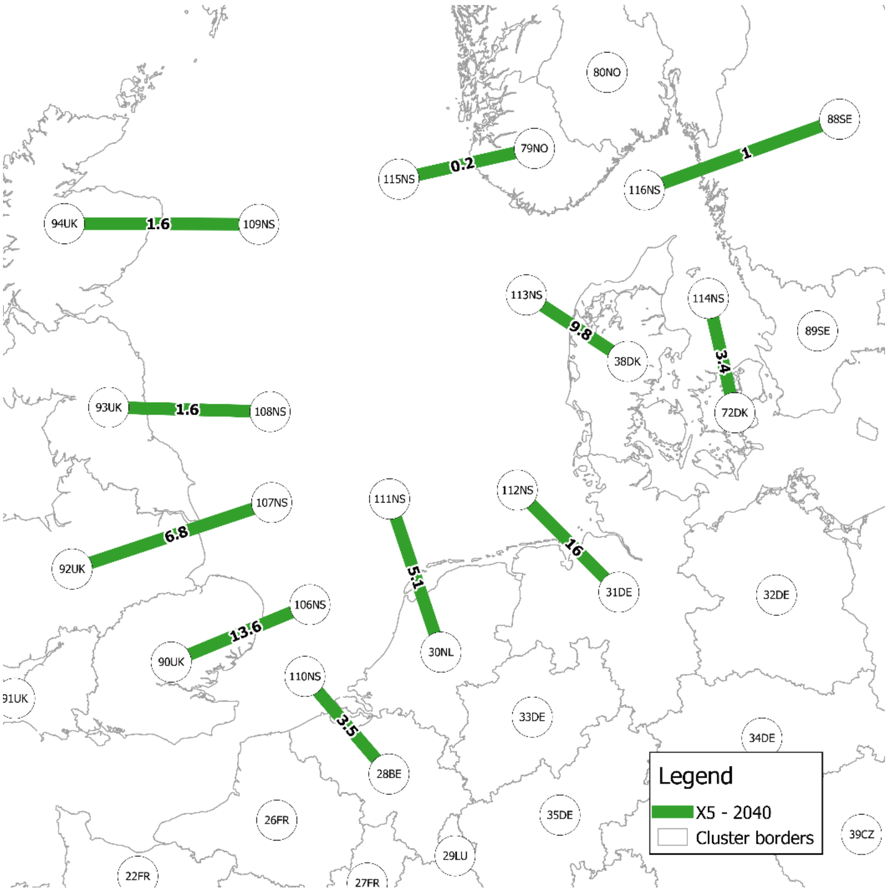


Figure 23: North Sea links in *Large Scale RES*

3.2.3. Connections with North Africa

The transmission capacities to North Africa for 2040 are obtained by scaling the transmission capacities for 2050 using the ratio of the installed power between 2040 and 2050 as a scaling factor.

Since the installed generation dedicated for exports to Europe is scenario dependant, the transmission capacities are scenario-specific (see Table 6 below).

Table 6: Links to North Africa

	Transmission capacity [MW]				
Link	**Large Scale RES**	**100% RES**	**Big & Market**	**Fossil & Nuclear**	**Small & Local**
102_ma – 13_pt	3 500	1 000	0	0	0
09_es - 102_ma	8 000	2 500	1 500	0	1 000
103_dz - 10_es	4 000	1 500	0	0	0
103_dz - 16_fr	8 000	2 500	1 500	0	1 000
103_dz - 98_it	7 500	2 500	1 000	0	500
104_tn - 56_it	5 500	2 000	500	0	500
105_ly - 56_it	5 500	2 000	1 500	0	500
105_ly - 69_gr	4 000	1 500	0	0	0
101_mi - 68_gr	1 500	1 500	1 500	0	1 500
101_mi - 69_gr	1 500	1 500	1 500	0	1 500
101_mi - 66_bg	1 000	1 000	1 000	0	1 000

3.2.4. Connections with the Middle East and Eastern Europe

The connections to the Middle East and Eastern Europe are the same as in WP2. They are listed in Table 7.

Table 7: Links to Middle East and Eastern Europe

Zone	Link	Transmission Capacity [MW] (same in all scenarios)
Eastern Europe	100_ea - 42_pl	1 000
	100_ea - 58_hu	700
	100_ea - 59_ro	700
	100_ea - 73_ee	1 000
	100_ea - 74_fi	70
	100_ea - 75_fi	1 400
	100_ea - 77_lt	1 900
	100_ea - 78_lv	400
Middle East	101_mi - 66_bg	1 500

	101_mi - 68_gr	2 000
	101_mi - 69_gr	2 000

3.3. Development of grid models for 2040

Grid models were developed by averaging the transmission requirements in 2050. The model is obtained by following this procedure:

- For each transmission requirement in 2050:
  1. Compute the average over the scenarios
  2. Multiply the average by a scaling factor.
  3. Round the result to the nearest gigawatt.
  4. If the rounded value is greater or equal to 2 GW, add the reinforcement to the model Otherwise, reject the reinforcement.

The procedure brings the following advantages:

- It considers the scenarios as equally probable.
- Exclusive alternative paths in 2050 are mixed in 2040.
- The most recurring reinforcement will be considered (least-regret strategy).

Two grid models were simulated with scaling factors 0.5 and 0.7. They are respectively called *Average 50%* and *Average 70%*. The transmission requirements of both grid models are listed in Annex 2 and are depicted in Figure 24 and Figure 25.

Figure 24: Maps of the reinforcements in the grid model *Average 50%* for 2040

Figure 25: Maps of the reinforcements in the grid model *Average 70%* for 2040

3.4. Simulation Results

3.4.1. Key indicators from simulations

Some Antares outputs give key information for the analysis of the adequacy in the system. The main indicators are described below.

- **Energy Not Supplied.** The energy not supplied (ENS) is the load that could not be supplied. It is an adequacy indicator: the greater the ENS value is, the lesser the system's adequacy is. The minimum amount is reached in copperplate simulation, where all transmission capacities are infinite.

- **Loss of Load Duration.** The loss of load duration (LOLD) is another adequacy indicator. It is the number of hours where load shedding must be used, i.e. the number of hours with a non-zero ENS value.
- **Spilled Energy.** Spilled energy is the key indicator for the use of must-run energy sources, like solar energy. If the full power produced by the must-run plants cannot be consumed, they must reduce their power output, and the result is spilled energy.
- **Redispatch.** In copperplate simulations, thermal generation is optimally dispatched to reach the lowest possible energy cost. While considering grid constraints, congestion occurs, and hence the dispatching is suboptimal. Thus, redispatch is the difference in generation between the grid simulation and the copperplate simulation. The two most important dispatchable plants are gas and nuclear, because gas plants produce rather expensive, and nuclear rather cheap energy.
- **Costs.** The main costs are the operating costs, i.e. the costs for energy generation. Moreover, a cost penalty (higher than all generation costs) is assigned to ENS, because it should be avoided.

A grid model should ensure adequacy, by avoiding ENS and LOLD, and enable cost effective energy production, by minimizing spillage and expensive redispatching.

3.4.2. Evaluation of simulation results

The simulation of the starting grid shows the main regional characteristics in Europe. Figure 26 and Figure 27 depict the localisation of ENS, spillage and redispatch for the scenario *Large Scale RES* in 2040. The grid models reinforce the connections between the outlying regions (Scandinavia, Spain, etc.) and the centre of Europe (France, Germany, Benelux, etc.). The outlying regions have an average energy excess in terms of spillage and negative nuclear redispatch; the central regions show an average energy deficit in terms of ENS and positive gas redispatch. Therefore, the grid models connect complementary regions to improve the adequacy and overall costs of the system.

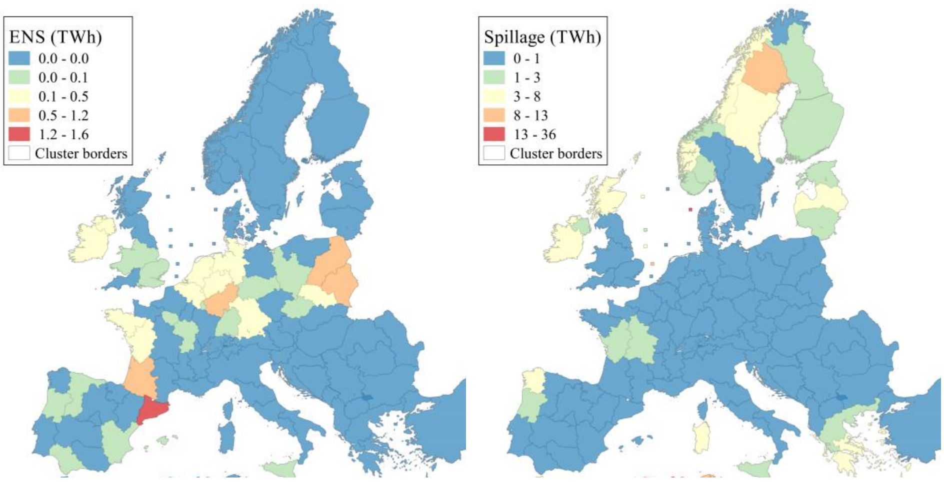


Figure 26: Repartition of energy not supplied and spillage in *Large Scale RES* (annual average)

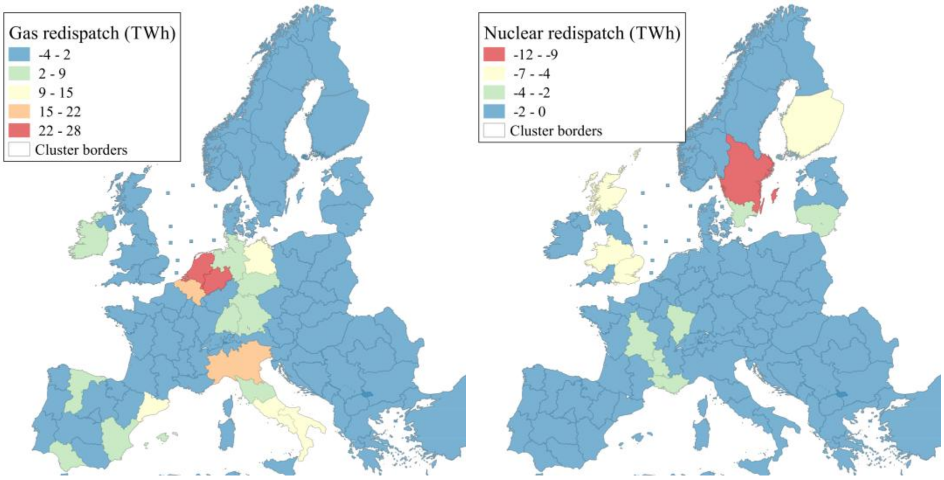
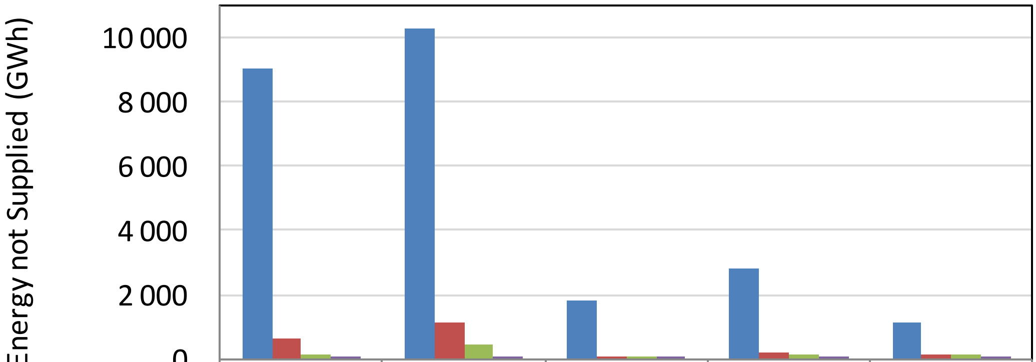


Figure 27: Repartition of gas and nuclear redispatch in *Large Scale RES* (annual average)

In the following paragraphs, all comparisons are done relative to the starting grid simulations.

The reduction in energy not supplied enabled by the grid model *Average 50%* is very high in all scenarios as shown Figure 28. It is reduced to about 10%. For the two scenarios *Fossil & Nuclear* and *Small & Local*, the value is near the absolute minimum obtained in copperplate simulations. With *Average 70%*, further improvements are visible for *Large Scale RES* and *100% RES*, but for the other scenarios, they are too small to be considered significant.

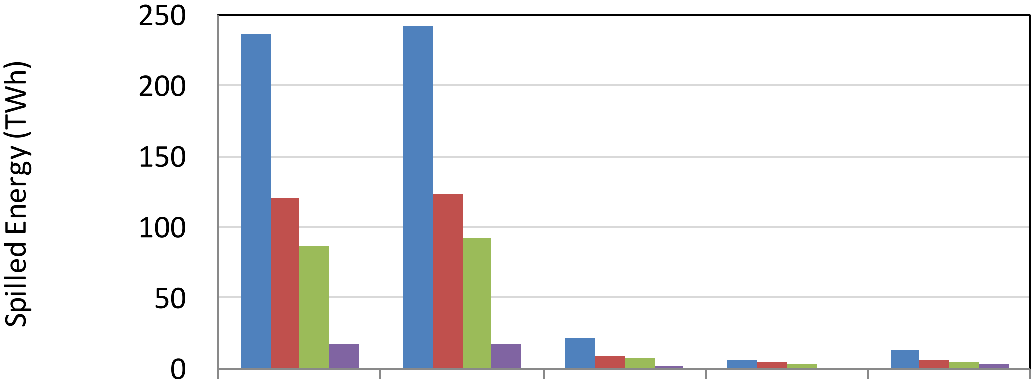


	Large Scale RES	100% RES	Big & Market	Fossil & Nuclear	Small & Local
Starting	9041	10295	1790	2804	1127
Average 50%	628	1121	57	230	127
Average 70%	157	430	36	156	111
Copperplate	0	0	0	71	68

Figure 28: Average annual energy not supplied for the whole system

The spillage is also reduced in all scenarios with the grid model *Average 50%* as shown in Figure 29. The scenarios *Large Scale RES* and *100% RES* are the most intensive in terms of renewable generation; their spilled energy is reduced to about 50%. The other scenarios also improve significantly, but the initial values are not as large. The grid model *Average 70%* improves further *Large Scale RES* and *100% RES*, but is almost useless for the other scenarios. Even with the

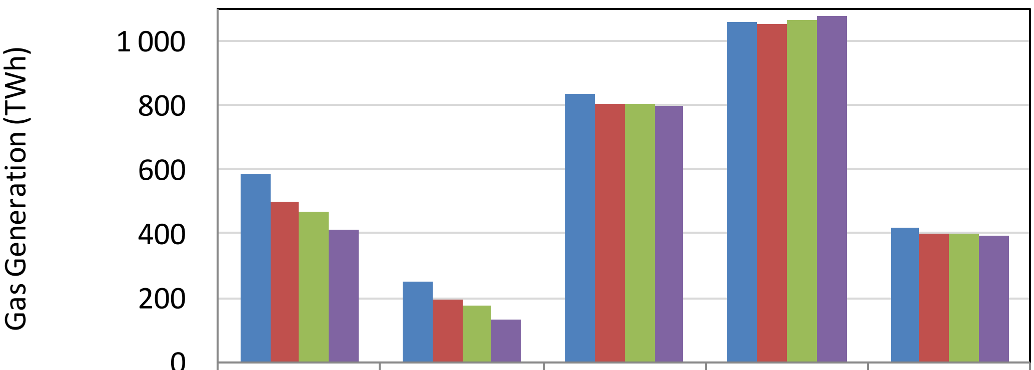
Average 70%, the scenarios *Large Scale RES* and *100% RES* face significant level of spillage. Further developments are already necessary in 2040 in those scenarios.



	Large Scale RES	100% RES	Big & Market	Fossil & Nuclear	Small & Local
Starting	237	242	21	6	13
Average 50%	120	124	9	4	6
Average 70%	87	92	8	3	5
Copperplate	17	18	1	0	3

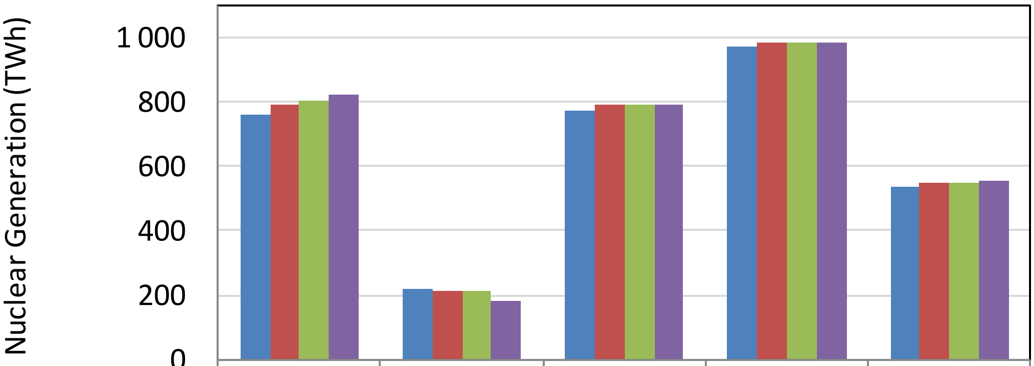
Figure 29: Average annual spilled energy for the whole system

The redispatch is also improved as shown in Figure 30 and Figure 31. The reinforcements reduce the expensive gas generation and increase the nuclear generation in all scenarios except *100% RES,* in which the nuclear generation is relatively expensive in comparison with the abundant and cheap renewable energy sources. Once again, the grid model *Average 70%* improves only *Large Scale RES* and *100% RES*.



	Large Scale RES	100% RES	Big & Market	Fossil & Nuclear	Small & Local
Starting	587	253	833	1057	415
Average 50%	499	193	806	1053	399
Average 70%	468	176	803	1064	397
Copperplate	411	131	800	1077	396

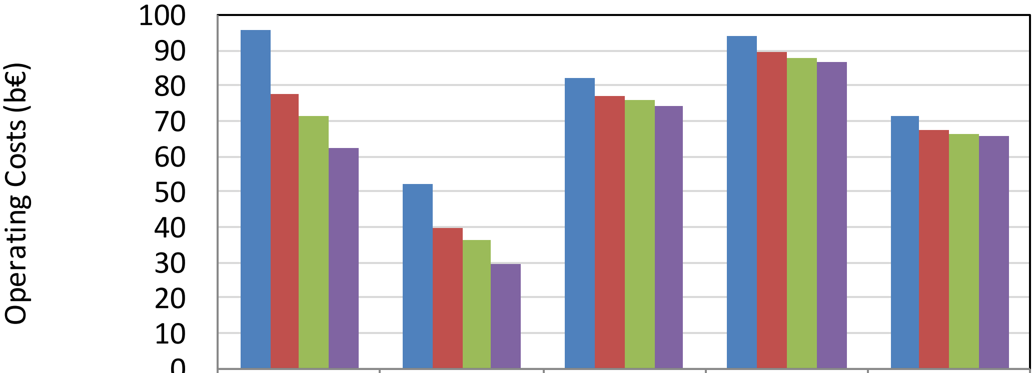
Figure 30: Average annual gas generation for the whole system



	Large Scale RES	100% RES	Big & Market	Fossil & Nuclear	Small & Local
Starting	763	221	773	973	538
Average 50%	792	215	788	985	549
Average 70%	804	213	792	986	551
Copperplate	822	185	794	986	552

Figure 31: Average annual nuclear generation for the whole system

The improvements in spilled energy and redispatch are reflected in the operating costs as shown in Figure 32. The gain in operating costs is the basis to estimate the investments costs of the system, and thus the profitability. *Large Scale RES* and *100% RES* are again the only scenarios to benefit significantly from *Average 70%*, and even more developments seem necessary in these scenarios in 2040 as the operating costs are still high compared to the copper plate case.



	Large Scale RES	100% RES	Big & Market	Fossil & Nuclear	Small & Local
Starting	96	52	82	94	72
Average 50%	77	40	77	89	67
Average 70%	72	36	76	88	67
Copperplate	63	30	74	87	65

Figure 32: Average annual operating costs for the whole system

3.5. Cost benefit analysis

3.5.1. Cost assessment of reinforcements

The costs are estimated for two strategies:

1. **Minimal costs:** All the reinforcements are done with overhead lines, except for subsea cables.
2. **Maximal costs:** All the reinforcements are carried out with underground and subsea cables.

The investment costs obtained with these two strategies are listed in Table 8. The total costs are converted to annuities by considering the annual discounted costs.

Table 8: Total investment costs for the two 2040 grid models

Total investment costs	Average 50%	Average 70%
Minimal investment costs [b€]	63.9	86.1
Maximal investment costs [b€]	96.0	141.3

3.5.2. Annual benefit assessment

The benefits can be separated in three categories.

1. **Saving in operating costs**: benefits from the improvement of the global cost of the energy produced. It is calculated as the difference in operating costs between the starting grid and a reinforced model.
2. **Saving in ENS and CO_2 costs**: benefits obtained from not running peaking units to cover the ENS. It is obtained using the generation costs and CO_2 costs of peaking units as ENS costs (200 €/MWh) instead of the standard value of e-Highway2050 (10 k€/MWh).
3. **Saving in ENS peak power**: benefits from not installing additional peaking units, corresponding to the investment costs to build peaking units.

The investment costs and benefits of the grid model *Average 50%* in Figure 33 show that the reinforcements are largely beneficial when considering minimal investment costs by using overhead lines. This is also true when considering the savings in fuel and CO_2 as only benefit. Regarding the maximal investment costs with cables only, the balance is slightly positive for *Big & Market* and even for *Fossil & Nuclear,* and *Small & Local*. In fact, the grid model is only profitable in these scenarios due to the savings in ENS fuel and peak power. *Large scale RES* and *100% RES* are still highly beneficial.

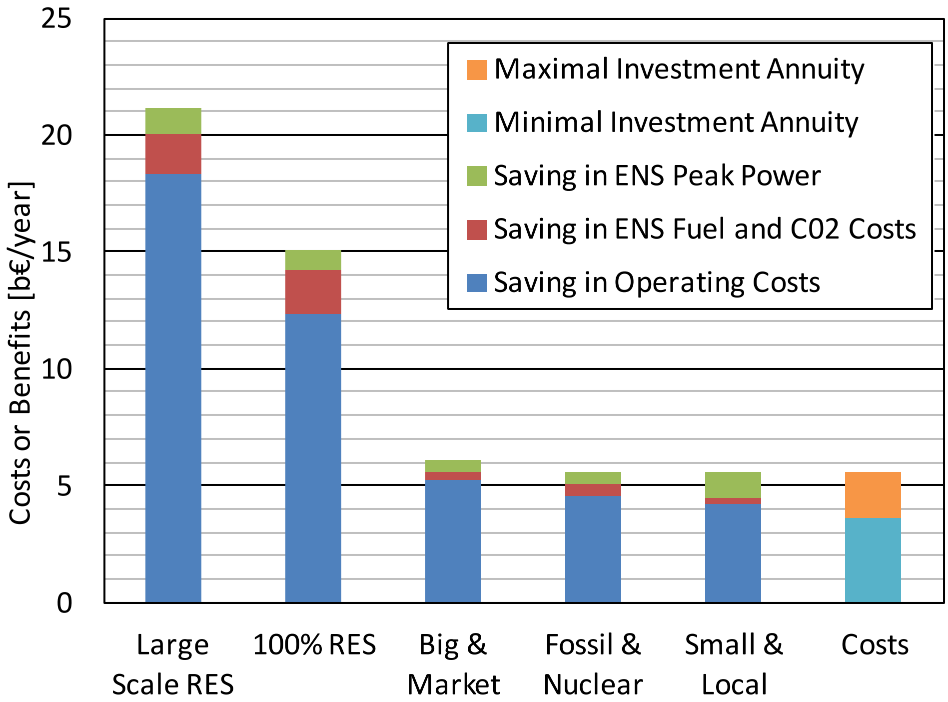


Figure 33: Benefits and Costs for the grid model *Average 50%*

The investment costs and benefits of the grid model *Average 70%* are shown in Figure 34. Although the benefits for *Large Scale RES* and *100% RES* are still highly above the costs of the grid, the investments are not profitable for the other scenarios, with costs exceeding benefits by more than 1 billion euros.

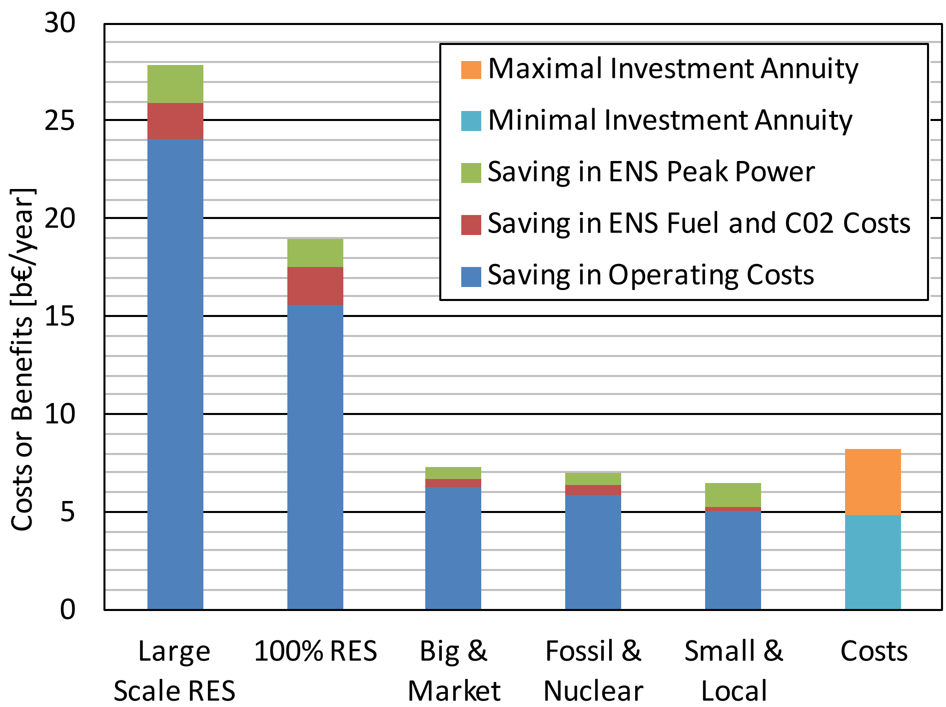


Figure 34: Benefits and Costs for the grid model *Average 70%*

3.5.3. Selection of final grid model

Both the grid models *Average 50%* and *Average 70%* increase the adequacy in the system. However, the latter is only profitable for *Large Scale RES* and *100% RES*, meaning that it is too expensive in the general case.

Therefore, the grid model *Average 70%* is rejected as a general purpose grid model, and the grid model *Average 50%* is chosen as final grid model for 2040.

However, if the energy mix steers more towards *Large Scale RES* and *100% RES* in the future, additional reinforcements of *Average 70%* could be considered as relevant investments.

4. Conclusions

In this report, the energy scenarios for the year 2040 were developed based on the TYNDP visions and the e-Highway2050 scenarios. For this purpose, five intermediate scenarios were quantified for 2040, taking into consideration different assumptions for demand, storage and generation. These data were studied both on country and cluster level. The 2040 data sets are available for each scenario in addition to the 2050 data sets.

Based on the 2040 scenarios, different least-regret grid models were developed and their investment costs and benefits were assessed. Through the application of this cost benefit analysis, the *Average 50%* grid model was selected, which is robust to all 2040 energy scenarios and in line with the 2050 grid architectures. For this purpose, the *Average 50%* grid is named *common 2040 grid* and the *Average 70%* grid is called the *extended 2040 grid*.

The *common 2040 grid* allows the reduction of energy not supplied by around 90% in all scenarios. Furthermore, the integration of renewable generation is facilitated by a reduction of spilled energy by around 50%. *Large Scale RES* and *100% RES* are the only scenarios to benefit significantly from the extended 2040 grid. Even more developments seem to be necessary in these scenarios until 2040.

The proposed reinforcements in the *common 2040 grid* cost less than 100 billion euros in total. They require around half of the investments required by 2050 in the scenarios *Small & local*, *Fossil & nuclear* and *Big & market*, thus heading for evenly distributed investments between 2030 and 2050. In the scenarios *Large Scale RES* and *100% RES*, additional reinforcements will be necessary in 2040 and 2050 to cover the needs. The *common grid model* is therefore a good “least-regret” trade-off between the five scenarios for 2040.

ANNEX 1 – Generation types in TYNDP and e-Highway2050

Table 9: Generation Types in TYNDP 2016 Draft

Flexibility	Generation Type
Dispatchable/ flexible Generation	Gas (with and without CCS)
	Hard Coal
	Lignite
	Nuclear
	Oil
	Biofuels
	Pumped storage*
Non-dispatchable/ inflexible Generation	Solar
	Wind (onshore and offshore*)
	Run-of-the-river hydro*
	Other RES (biomass, renewable waste, tidal, wave, geothermal)
	Other non-RES (non-renewable CHP, waste and other generation)

Table 10: Generation Types in e-Highway2050

Flexibility	Generation Type
Dispatchable/ flexible Generation	Gas (CCGT with and without CCS)
	OCGT, peak units
	Hard Coal (with and without CCS)
	Lignite (with and without CCS)
	Nuclear
	Biomass (2 types)
	Pumped storage
Non-dispatchable/ inflexible Generation	Wind (onshore + offshore, North Sea)
	Solar (photovoltaics, concentrated solar power)
	Hydro (run-of-the-river, hydro with reservoir)

ANNEX 2 – Transmission Requirements in 2040

		Transmission requirements [MW]	
Links	**Length [km]**	**Average 50%**	**Average 70%**
04_es - 14_fr	238	3 000	4 000
06_es - 11_es	365	2 000	3 000
06_es - 15_fr	272	5 000	6 000
106_ns - 110_ns	105	-	2 000
112_ns - 113_ns	198	-	3 000
14_fr - 15_fr	189	2 000	3 000
14_fr - 17_fr	308	5 000	6 000
15_fr - 16_fr	254	2 000	2 000
17_fr - 22_fr	248	5 000	7 000
21_fr - 96_ie	682	2 000	2 000
22_fr - 90_uk	313	4 000	6 000
26_fr - 90_uk	275	4 000	5 000
28_be - 90_uk	353	-	2 000
30_nl - 79_no	739	3 000	4 000
31_de - 33_de	219	-	2 000
31_de - 38_dk	333	2 000	3 000
31_de - 79_no	652	3 000	4 000
32_DE - 89_SE	386	3 000	4 000
34_de - 44_pl	296	2 000	2 000
37_de - 49_at	198	-	2 000
41_pl - 77_lt	349	3 000	4 000
49_at - 52_it	262	2 000	2 000
52_it - 53_it	264	3 000	4 000
53_it - 54_it	192	3 000	4 000
54_it - 55_it	301	3 000	4 000
54_it - 98_it	429	2 000	2 000
55_it - 56_it	357	2 000	3 000
55_it - 68_gr	463	3 000	4 000

73_ee - 75_fi	404	2 000	3 000
73_ee - 78_lv	204	2 000	3 000
77_lt - 78_lv	182	2 000	3 000
79_no - 80_no	152	-	2 000
79_no - 81_no	216	3 000	4 000
81_no - 83_no	283	2 000	3 000
81_no - 90_uk	1 066	-	2 000
83_no - 84_no	488	2 000	2 000
86_se - 87_se	407	2 000	3 000
87_se - 88_se	499	3 000	5 000
88_se - 89_se	307	3 000	4 000
90_uk - 92_uk	196	5 000	7 000
92_uk - 93_uk	239	4 000	5 000
93_uk - 94_uk	273	3 000	4 000

ANNEX 3 – Grid Development Tools

A toolbox was developed using Matlab for parallelisation of simulations, data processing and visualisation.

- **Parallelisation.** Antares does not enable natively efficient parallel computing necessary to fully exploit the available computing power. However, since MC years are independent, they can be splitted in groups and simulated simultaneously by parallel solvers. Scripts were written to configure automatically Antares simulations for a given number of parallel instances.
- **Data Processing.** To exploit the data processing and visualisation capabilities of Matlab, import scripts were written to extract the Antares outputs into an easy to use file format. It was necessary to reconstruct the synthetic outputs lost in the parallelisation process, but also allowed detailed data analysis and visualisation, including more computation-intensive statistical analysis, that would have been otherwise more time consuming. With the raw output of Antares, the simulations results take up to 40 GB of disk space per study. Through a more efficient storage, the data size could be reduced by 90%.

Additionally, the toolbox was interfaced with the *PowerFlowAnalyzer* (PFA)[1], which provides handy features for network state visualisation and comparison. The general architecture is shown in Figure 35. *Automation Tools* consist of the parallelisation scripts; *Data Manipulation* and *Visualisation* take care of the data processing.

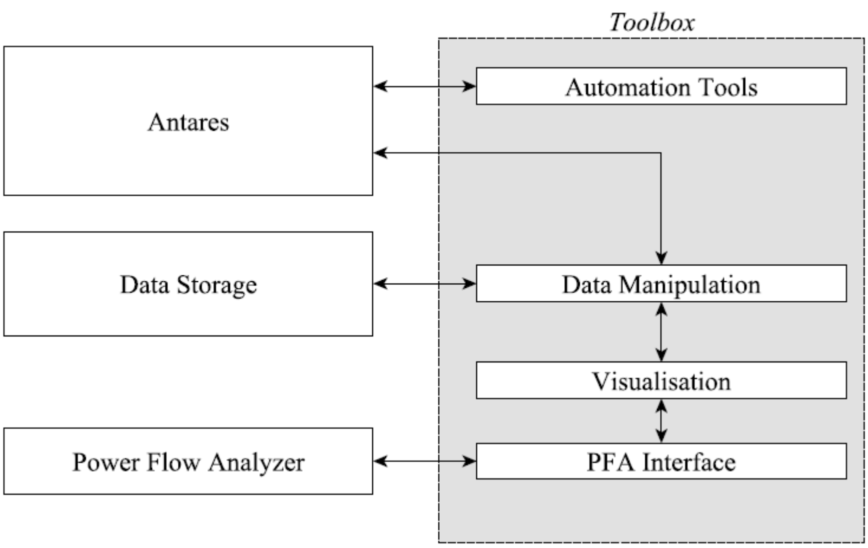


Figure 35: Structure of the toolbox

[1] PFA was developed at the SENSE department at the TU Berlin.

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