Ten-Year Network Development Plan 2020

Completing the map
Power system needs in 2030 and 2040

November 2020 · Version for public consultation

entsoe

About ENTSO-E

ENTSO-E, the European Network of Transmission System Operators for Electricity, represents 42 electricity transmission system operators (TSOs) from 35 countries across Europe. ENTSO-E was registered in European law in 2009 and given legal mandates since then.

The role of Transmission System Operators has considerably evolved with the Third Energy Package. Due to unbundling and the liberalisation of the energy market TSOs have become the meeting place for the various players to interact on the market place.

ENTSO-E members share the objective of setting up the internal energy market and ensuring its optimal functioning, and of supporting the ambitious European energy and climate agenda. One of the important issues on today's agenda is the integration of a high degree of renewables in Europe's energy system, the development of flexibility, and a much more customer-centric approach than in the past.

ENTSO-E is committed to develop the most suitable responses to the challenge of a changing power system while maintaining security of supply. Innovation, a market-based approach, customer focus, stakeholder focus, security of supply, flexibility, and regional cooperation are key to ENTSO-E's agenda.

ENTSO-E is contributing to build the world's largest electricity market, the benefits of which will not only be felt by all those in the energy sector but also by Europe's overall economy, today and in the future.

Transparency is a key principle for ENTSO-E, and requires a constant listening, learning and improvement.

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Highlights

- Europe's power system is evolving rapidly. ENTSO-E's **System Needs study** shows where action is needed by 2040 to ensure continuous access to electricity throughout Europe and deliver on the climate agenda.
- In addition to the **35 GW** of cross-border transmission capacity reinforcements by 2025 that are already well-advanced, the System Needs study finds that **50 GW** would be cost efficient between 2025 and 2030 and 43 additional GW by 2040. Investing 1.3 bn€/year between 2025 and 2030 translates into a decrease of generation costs of 4 bn€/year, while investing 3.4 bn€/year between 2025 and 2040 decreases generation costs by 10 bn€/year.
- Addressing system needs puts Europe on track to realize the **Green Deal,** with 110 TWh of curtailed energy saved and 55 Mtons of CO_2 emissions avoided each year until 2040. Market integration would progress, with price convergence increasing between bidding zones thanks to an additional 467 TWh/year of cross border exchanges by 2040.
- The System Needs study expresses needs in terms of cross-border transmission capacity increase and identifies the most cost-efficient combination of increases, but it does not mean that the identified set of increases are the only solution. The **identified needs can be addressed in multiple ways** such as increased transmission capacity, storage, hybrid offshore infrastructure, smart grids and power to gas.
- Increased cross-border exchanges and distributed generation will also create stresses for national grids and trigger needs for **internal reinforcements.** Internal reinforcements already identified in previous studies and related to cross-border needs, especially for the 2030 horizon, have been considered as part of the estimated cost for capacity increases, but once the needs turn into projects, they will need to be confirmed and new needs for internal reinforcements can also arise.
- Investing in infrastructure will be key to support the economy in the post COVID era, where the goal of developing Europe towards a decarbonized economy is an opportunity not only to fulfil the ambitious European objectives, but also to support the European industry. Addressing the identified needs by 2040 would represent **45 bn € of investment, translating directly into jobs and growth.**
- Some of the identified needs are already covered by concrete TYNDP projects, while about 50 GW do not correspond to existing projects in the 2040 horizon. All options should be considered when these needs turn into projects and **coordinated planning** will be needed **across sectors.** This is especially important in the subsequent steps where further analyses in terms of environmental impact, viability, benefits beyond socio-economic welfare and refined costs are carried out in order to complement the definition of the best project portfolio.
- The energy transition is also creating needs for system operations. Trends show a reduction of system inertia due to increasing integration of renewable energy sources and distributed generation, leading to higher vulnerability of the system to frequency mismatches. **Flexibility** options will gain in importance, both at generation and demand level, and in this context the role of TSOs in securing **network stability** will be key.

2020

Today's power system

35 GW of cross-border capacity increases in construction or planned until 2025

If Europe stopped investing in the grid after 2025

BY 2030

49 TWh/year curtailed energy

591 Mton/year CO_2 emissions

51 bn €/year generation cost

BY 2040

244 TWh/year curtailed energy

446 Mton/year CO_2 emissions

65 bn €/year generation cost

With an expanded grid after 2025

With 50 GW of capacity increase after 2025, representing a cost of 1.3 bn € per year

BY 2030

28 TWh/year curtailed energy

630 Mton/year CO_2 emissions

48 bn €/year generation cost

With 93 GW of capacity increase after 2025, representing a cost of 3.4 bn € per year

BY 2040

134 TWh/year curtailed energy

391 Mton/year CO_2 emissions

55 bn €/year generation cost

How to read this report

A **Q & A** answers frequently asked questions.

The **Introduction** presents the context behind the System Needs study.

Chapter 1 presents the needs identified in 2030 and 2040.

Chapter 2 elaborates on the benefits of addressing those needs, for Europe's climate ambition, market integration and security of supply. To that end, a system where needs are addressed is compared to an alternative future where Europe would stop investing in the grid after 2025.

Chapter 3 considers the theoretical case where there would not be any capacity constraint on electricity transmission. This exercise sheds light on the absolute maximum benefits that could be captured by increasing network capacity.

Chapter 4 compares the findings of this edition of the System needs study to those of the 2018 exercise.

Chapter 5 investigates new needs appearing with the energy transition: technical challenges for system operations caused by a combination of trends including more renewable energy sources at all voltage levels, more power electronics, a very variable mix of generation and large and highly variable power flows.

Chapter 6 concludes with the next steps after the System needs study release.

Chapter 7 presents the methodology of the study and is completed by Appendices.

How to use this interactive document

To help you find the information you need quickly and easily we have made this an interactive document.

Home button
This will take you to the contents page. You can click on the titles to navigate to a chapter.

Arrows
Click on the arrows to move backwards or forwards a page.

Glossary
You will find a link to the glossary on each page.

Hyperlinks
Hyperlinks are highlighted in bold text and underlined throughout the report. You can click on them to access further information.

Visualise the data
tyndp.entsoe.eu/system-needs

Contents

Q&A

What are system needs?

System needs show borders/areas where new solutions for electricity exchange are needed to reach decarbonisation targets and keep security and costs under control. This study focuses on needs beyond the next anticipated wave of cross-border grid investments (35 GW by 2025). They use the National Trend scenarios for 2030 and 2040, which means that the system needs identified exist in a world where significant uptake of renewable energy sources and system flexibility already happened.

System needs or transmission needs?

The System needs study describes needs, not the solutions to the needs. The study uses interconnection transmission capacity to express the needs because it is based on electricity TSOs' expertise, data and models, but it does not mean that electricity infrastructure is the unique solution. The methodology only provides indication of where, for example, market integration could be improved, but it cannot prioritise between possible solutions. ENTSO-E expects that addressing tomorrow's challenges will require the parallel development of all possible solutions, including for example storage, the role of prosumers and generation, in addition to reinforcing the transmission grid.

Where do system needs exist?

The study finds needs everywhere in Europe, with a total of 50 GW of needs on close to 40 borders in 2030 and 43 additional GW on more than 55 borders in 2040. Addressing system needs would put Europe on track to realize the Green Deal, with 110 TWh of curtailed energy saved each year and 55 Mtons of CO_2 emissions avoided each year until 2040. Market integration would progress, with price convergence increasing between bidding zones thanks to an additional 467 TWh/year of cross border exchanges by 2040. Investing 1.3 bn € each year between 2025 and 2030 translates into a decrease of generation costs of 4 bn € per year, while investing 3.4 bn € each year between 2025 and 2040 decreases generation costs by 10 bn € per year.

The System needs study considers only cross-border capacities, does this mean that there are no needs within countries?

There are needs to develop internal networks within countries. Although internal needs are not the focus of the System needs study, they are a direct implication of the results: increasing capacity on a border will require a reinforcement of the internal network of the concerned countries in most cases. This is because electricity tends to transit, crossing countries on its way from places with high generation from renewable energy sources to places with high load, or from bidding zones with lower prices to bidding zones with higher prices.

Will TSOs plan the future grid based on identified system needs?

The System needs study is not a network development plan. It is a study that investigates one particular dimension of the future, which is where increases in network capacity would be the most cost-efficient from a pan-European perspective. To plan future network development, TSOs consider a multitude of aspects, including socio-economic welfare but also other benefits of projects (for instance in term of security of supply or reductions of CO_2 emissions) and other scenarios of evolution of the energy system. TSOs will use the study's findings as a tool to develop future National Development Plans, in complement to national and regional planning studies.

Why does the System Needs study investigate the National Trends scenario?

The future investigated by the study is the National Trends scenario, which aims at reflecting the commitments of Member States to meet the targets set by the European Union in term of efficiency and GHG emissions reduction for the energy sector. At country level, National Trends is aligned with the National Energy and Climate Plans (NECPs) of the respective Member States, which translate the European targets to country specific objectives for 2030. What is necessary to achieve the objectives of the NECPs will be even more necessary for the Green Deal, and it is anticipated that NECPs in future will evolve towards Green Deal objectives.

Other TYNDP 2020 scenarios – the COP21 scenarios Distributed Energy and Global Ambition, and a Current Trends sensitivity – will be investigated in the cost-benefit analysis of projects.

How does the TYNDP 2020 project portfolio cover the identified needs?

Of the 93 GW of needs identified between 2025 and 2040, transmission projects currently under conception or development address about 43 GW (on some borders, more than one project compete sometimes to address the same need). Other technologies such as storage could also address these needs.

The remaining 50 GW of needs are left to be addressed, by all possible means. This is a considerable investment gap to be tackled until 2040. The solution will include a combination of technologies across sectors and will require coordinated planning. To prepare for the future 'system of systems', ENTSO-E has developed a **Roadmap** for coordinated multi-sectorial planning of infrastructure. The Roadmap will serve as an umbrella for future planning activities, to improve the consideration of smart sector integration in the infrastructure planning process and will identify needs for dual or multiple-sector assessment of infrastructure projects.

There is no system need identified on a border, does it mean that no infrastructure should be built?

The System needs is a partial exercise that investigates one specific dimension of future system needs, which is where increasing cross-border capacity would be most cost-efficient. Planning electricity transmission infrastructure requires to consider a whole area of indicators, including costs but also for example benefits of projects in terms of frequency system stability, reduction of CO_2 emissions and other greenhouse gases, etc. It is therefore possible that a project receives a positive cost-benefit analysis even when it is on a border that is not included in the best combination of capacity increases identified by the System Needs study.

Will the System needs study results be considered by the European Commission to select Projects of Common Interest?

Regulation (EU) 347/2013 makes the TYNDP the basis for the selection of Projects of Common Interest (PCIs). However, the process to select European Projects of Common Interest is under the responsibility of the regional groups led by the European Commission, who ultimately decides on the material to be taken into consideration. ENTSO-E stands ready to provide the European Commission with all required information. In prevision of the launch of the 5th PCI process in Q4 2020, brief summaries of the needs in each PCI corridor in the 2030 horizon will be made available in September.

What is the expected impact of the revised Electricity Regulation on the System needs study?

Regulation (EU) 2019/943 on the internal market for electricity specifies a minimum available cross-border capacity to be made available to market participants. Depending on the modalities of enforcement of this rule, needs for grid reinforcement might be reduced, as already more market capacity could be available based on existing cross-border interconnections. This has not been investigated in this edition of the System needs study but may be considered in future editions.

How are stakeholders involved in the identification of system needs?

The System needs package, including this report and the six Regional investment plans published alongside it, will be submitted to a public consultation alongside the rest of the TYNDP 2020 package. The consultation is foreseen to begin by early November 2020 and to last six weeks. To further engage with stakeholders, a webinar took place on 28 September 2020.

Stakeholders comments will serve to improve the reports. Comments regarding the methodology itself will be taken into account to improve the future editions of the System needs study, as time does not allow to re-run the study. Stakeholders wishing to discuss how the assessment of system needs could be further improved are welcome to contact ENTSO-E at **tyndp@entsoe.eu**.

In January 2021, the entire TYNDP 2020 package will be submitted to ACER for a formal Opinion. ACER's comments will be implemented as far as possible in this edition of the System needs study, or alternatively considered for implementation in the 2022 exercise.

Do identified system needs stay the same as in the previous system needs study?

The 2020 system needs study identified significantly higher needs for the 2040 horizon than the 2018 exercise, with a global increase of 37 additional GW of cross-border capacity increases. The benefits captured by the needs identified in 2020 are also higher in terms of variable generation cost, avoided CO_2 reduction and avoided curtailment. The differences between the 2018 and 2020 results lie mainly in the scenario used. Despite these differences, ENTSO-E considers that the results are consistent enough and confirm the usefulness of the zonal methodology approach.

Are the data and tools to replicate the System needs study available?

The data used for the System needs study includes:

- Datasets of scenarios National Trends 2030 and National Trends 2040 **Download**
- List of candidate projects and cost assumptions (available in Appendix 3)
- Network dataset of the TYNDP 2020: it will be made available in aggregated form in Q4 2020. The network dataset of the TYNDP 2018 is accessible **upon request**.

The tool used for this study is Antares, which is an open source tool, with an expansion module publicly available (antaresXpansion).

Introduction

How should the electricity grid look like in 2040 to create maximum value for Europeans, ensure continuous access to electricity throughout Europe and deliver on the climate agenda? What would be the cost for Europeans of not having the right electricity infrastructure by 2040? Which future challenges will be created by the expected high increase of renewable generation units, in part small and distributed, with variable production? The cost to society of an inadequate network is considerable due to the central role that a reliable energy supply plays for society.

What is the Identification of System Needs?

The identification of system needs study investigates where improving the electricity flow throughout Europe could bring benefits to Europeans. The present report investigates needs in the 2040 and 2030 horizons. For example: where could CO_2 emissions be reduced? Where could the curtailed electricity from renewable energy sources be used? Where could the electricity price between neighbouring countries be more aligned? The study also assesses the cost of not investing in the needed infrastructure. The System needs study is carried out by ENTSO-E biannually and forms part of the Ten-Year Network Development Plan (TYNDP) 2020 package.

An essential step in Europe's long-term electricity infrastructure planning

The TYNDP is a long-term plan on how the electricity transmission grid is expected to evolve in Europe to implement the EU energy. Identifying the system needs is the second step in the development of the TYNDP.

The TYNDP 2020 scenarios developed jointly by ENTSO-E and its gas counterpart ENTSOG are described in the **Scenarios report** published in June 2020. Following the collection of projects from project promoters in November 2019, the TYNDP 2020 will perform a cost-benefit analysis of 171 transmission and storage **projects** and evaluate how they contribute to meeting the system needs for 2030.

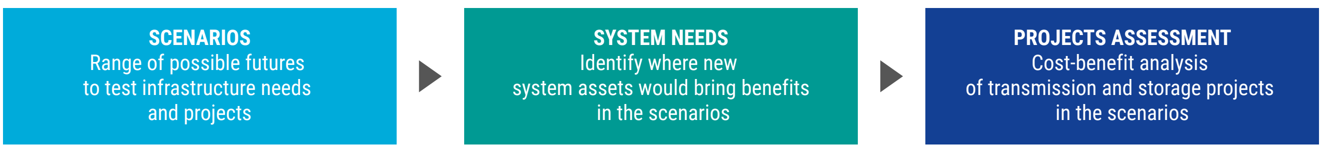


Figure 0.1 – The three main steps of the TYNDP process

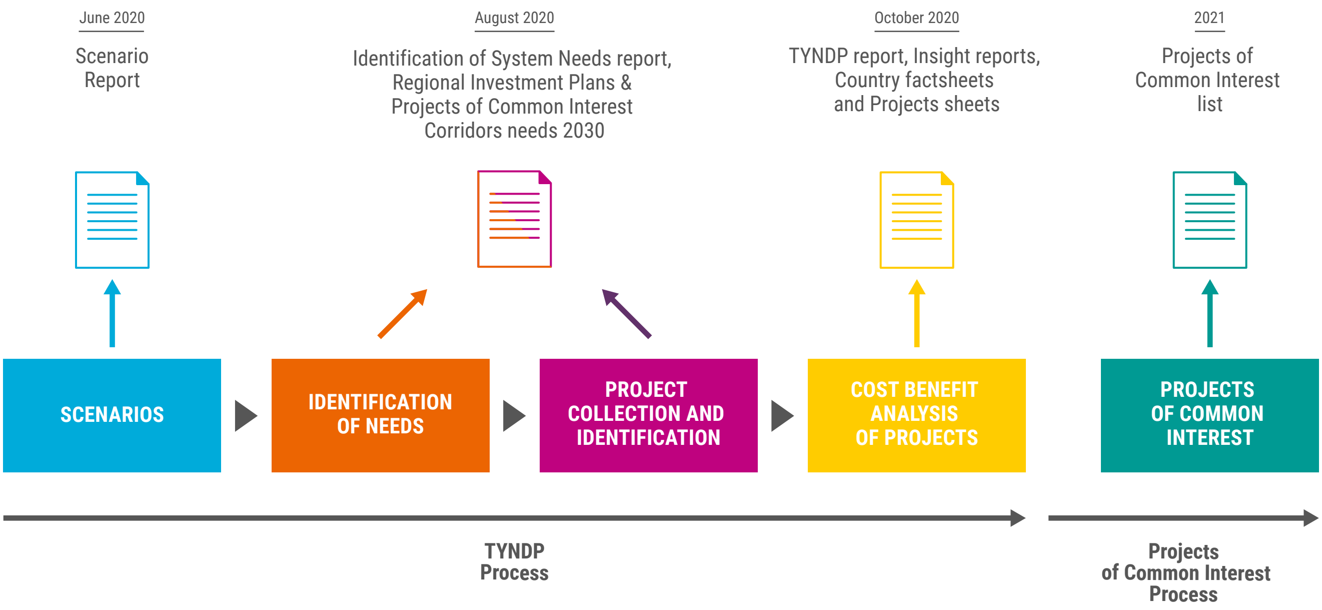


Figure 0.2 – TYNDP and Projects of Common Interest processes and their key deliverables

Results of the System needs study will lead to the development of new projects addressing newly identified needs. These projects are anticipated in future national development plans and TYNDPs. To consider these projects already in the TYNDP 2020, ENTSO-E is opening a second project-submission window on the date of publication of this report, opened only to future projects commissioning after 2035 addressing system needs.

Running the System needs study every two years enables the needs behind projects to be monitored. As and when needs change, because new scenarios are being investigated, project promoters may redefine or even terminate projects, also considering economic profitability due to market developments.

Alongside this System needs report, ENTSO-E publishes six regional investment plans diving into details of the specific needs at regional level for 2040 and including additional sensitivity studies. ENTSO-E will also release later this summer four brief reports providing an overview of the needs for 2030 in each of the four TEN-E electricity priority corridors.

An evolving tool to enable the energy transition

The System needs study is an evolving tool to manage increasing uncertainty in the context of the energy transition and EU Green Deal. Its methodology and scope have greatly improved compared to the previous System needs release, with the use of a zonal model for the 2040 horizon allowing for increased granularity of the results and the expansion of the scope to the 2030 horizon with a Net Transfer Capacity model.

The methodology and assumptions are further described in Chapter 7.

1 What are system needs by 2030 and 2040?

The 2030 and 2040 scenarios are challenging from many points of view, including for the electricity transmission network. The change in the generation portfolio, with increased solar and onshore wind generation in the south of Europe and onshore and offshore wind generation in the north, in parallel with the decommissioning of thermal units, cause higher and variable transit flows across Europe. These flows must be accommodated by the grid to capture all the benefits of the energy transition.

This new challenge brought by the evolution of generation portfolios is already partially covered by an increase of flexible assets within the scenario National Trends. Indeed, from 2025 to 2040 battery capacity in Europe increases by 60 GW, Demand Side Response by 10 GW and Power-to-Gas by 3.5 GW. System needs go beyond this point in order to provide a secure, cheap and decarbonized electricity at all time and in all places.

Methodology: Identifying capacity increases

To analyze system needs by 2030 and 2040, ENTSO-E determined the combination of potential increases in cross-border network capacity that minimizes the total system costs, composed of total network investment (including costs of related necessary internal reinforcements for most borders) and generation costs. To do that, a panel of possible network increases was proposed to an optimizer, who identified the most cost-efficient combination. To take into account the mutual influence of capacity increases, the analysis was performed simultaneously for all borders. The combination of network increases minimizing costs identified through this process is hereafter called **'SEW-based needs'** where SEW stands for socio-economic welfare. Further explanation on the methodology is provided in Chapter 7.

The results of the System Needs study clearly show the high economic interest of investing in the grid to support the energy transition.

- By 2025, about 35 GW of new cross-border reinforcements, depicted in Figure 1.1, are expected to be built in addition to the 2020 grid. These very mature projects (some of them are already under construction), already justified in previous TYNDP releases, correspond to the best view of the 2025 European transmission grid. In consequence they are not questioned in the study and serve as the starting grid for the analysis.
- By 2030, the study finds that 50 additional GW of cross border reinforcements would be cost efficient to support the electric system. These capacity increases represent about 17 bn € of investment in the European transmission grid. This considerable amount of reinforcements can be explained by a conservative approach to define the 2025 reference grid. As a result, by 2030, in addition to accompanying the evolution of the electric system occurring between 2025 and 2030, a compensation of the delay in grid reinforcement could be necessary. Slightly more than half of these needs could be covered by existing TYNDP projects while the remaining part are currently only conceptual.
- By 2040, 43 GW of additional cross-border investments on top of the increases identified for 2030 would support the evolution of the electricity mix. These capacity increases represent about 28 bn € of investment. These needs are only partly covered by concrete TYNDP projects (14 GW).

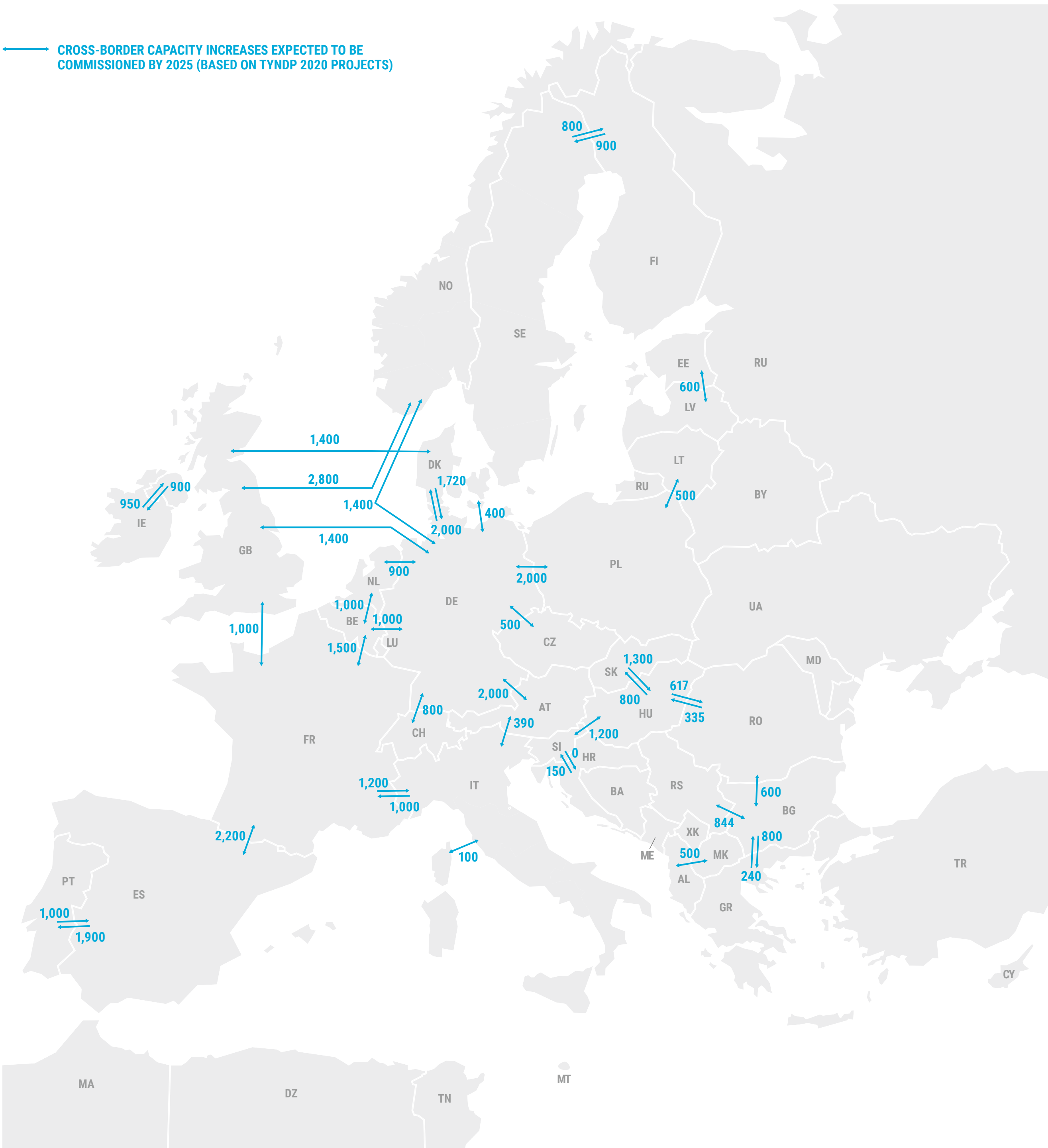


Figure 1.1 – Cross-border capacity increases, corresponding to projects under construction or in permitting phase and expected to become effective by 2025. Identified needs in 2030 and 2040 come in addition to these capacity increases.

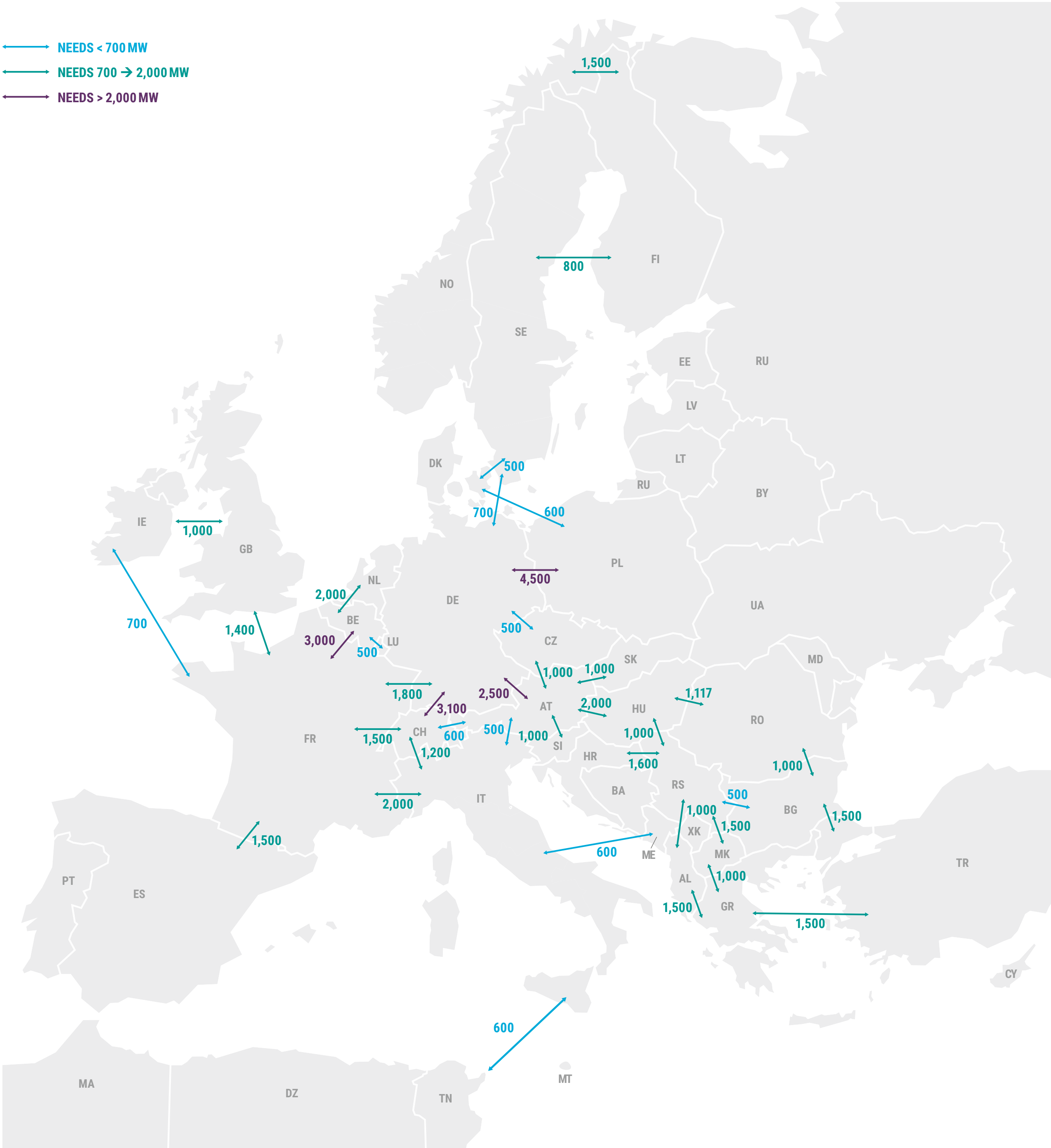


Figure 1.2 – Needs for capacity increases identified in the 2030 horizon, additional to the 2025 network (SEW based needs 2030)*.

* Ireland and Northern Ireland form one wholesale electricity market area known as the Single Electricity Market (SEM). Therefore, the needs identified between the island of Ireland and Great Britain could be satisfied by capacity increases in either Ireland or Northern Ireland.

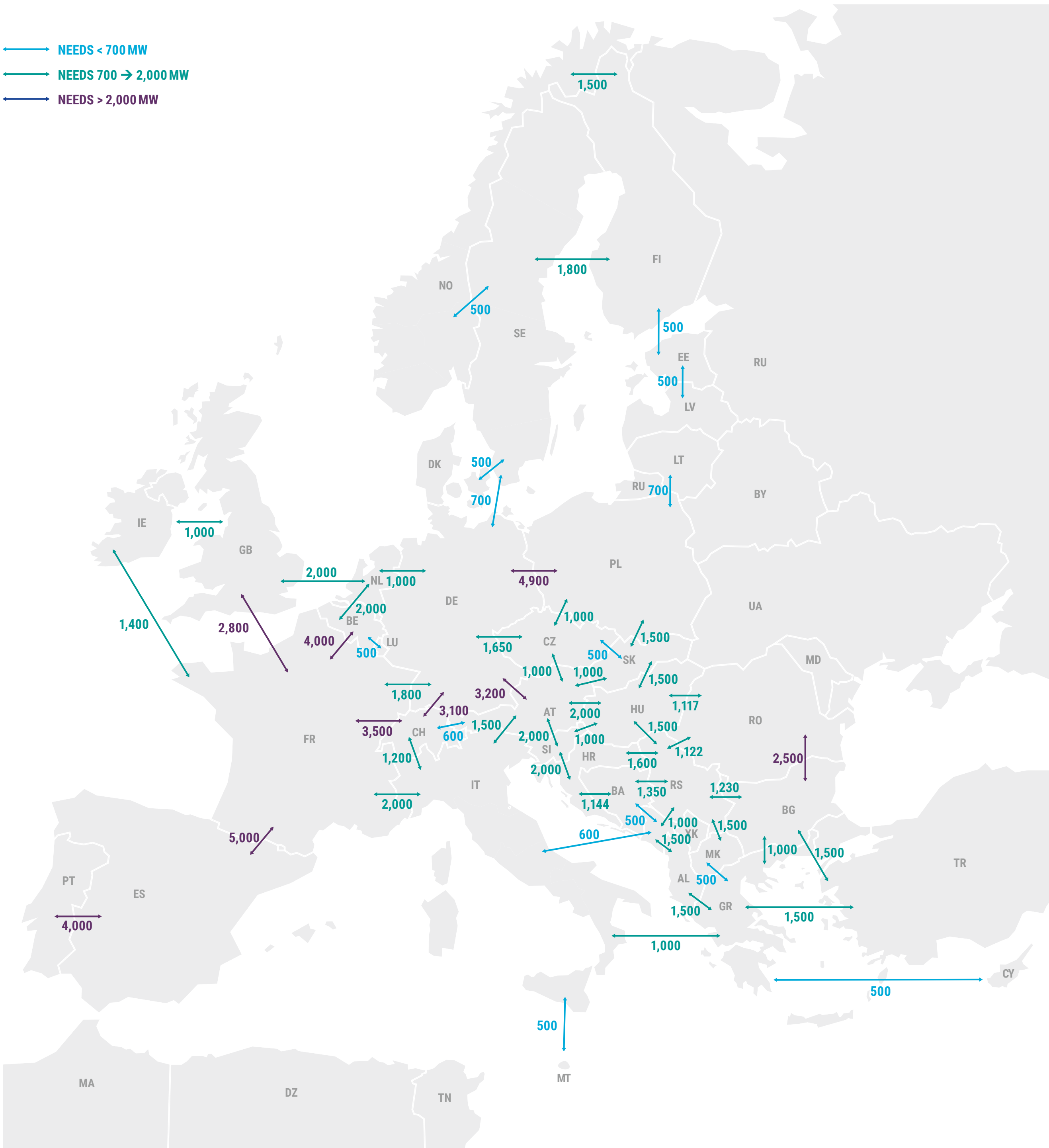


Figure 1.3 – Needs for capacity increases identified in the 2040 horizon, additional to the 2025 network (SEW based needs 2040)*.

The needs identified as transmission capacity increases are located all over Europe. For 2030, the highest identified capacity increases are located on the German borders with Poland, Switzerland and Austria, and on the Belgium-France border, although there are many other needs to accommodate flows between Southwest and Central Europe (Spain-France and other French borders) and between Eastern and Central Europe (from Turkey through the Balkan countries up to Austria) and to integrate the Italian peninsula.

For 2040, the highest identified capacity increases are located in the Iberian Peninsula, especially on the France-Spain border with also a significant increase on the Portugal-Spain border. As in 2030, the German borders with Poland, Switzerland and Austria and the Belgium-France border are among the borders with the highest needs. However, in 2040 the French borders to Switzerland and the United Kingdom will also require capacity increases. In Eastern Europe, where cross-border capacities are generally lower, high needs have been identified on the Bulgaria-Romania border. Additional needs require to accommodate North-South flows between the Nordic countries through continental Europe to the Balkans, between UK and Ireland with the Continent and to integrate the Italian peninsula. Readers are invited to refer to the Regional Investment Plans for further analysis on specific capacity increases identified in Figures 1.2 and 1.3.

The impact of these reinforcements on the power system is considerable and their benefits far outweigh their costs. Additional cross-border exchange capacity allows to better mutualize generation capacity among countries as well as their differences in load profile. Chapter 2 details the impact of addressing the SEW-based needs on a series of indicators, including CO_2 emissions, curtailed energy, and marginal costs and compares these benefits to a hypothetical situation where Europe would stop investing in the grid after 2025.

As a next step, the needs found in this study will be confronted to concrete projects (existing or new) in the TYNDP 2020 project portfolio, as submitted by project promoters. The details of the project (capacity, location, technology...) will allow to estimate precise costs and benefits in a variety of scenarios and assess if the investment is indeed economically beneficial. The evolution of the energy mix and of the development of the grid, as well as the numerous impacts projects have on the power system beyond lowering the generation costs, have to be taken into account at each investment step through a dedicated cost-benefit analysis.

The SEW-based capacity increases, one solution among others

The SEW-based needs are a depiction of the needed effective cross-border transfer capacity increases necessary for a cost-optimized operation of the 2030 and 2040 system. It is important to note that considerations in terms of system resilience, system security, or other societal benefits are not included in this analysis. The cost-optimized operation of the 2030/2040 system is a function of the cost estimates for the cross-border capacity increases and the generation costs.

While the optimisation process behind this analysis has aimed at a robust identification of the cost-optimized system, the inherent complexity of the power system implies that different depictions of the needed cross-border capacity increases lead to results of practically similar benefits. Figures 1.4 and 1.5 capture this effect for those borders where a different SEW-based solution would lead to similar benefits and would therefore suggest that it is a well-identified need without being part of the SEW-based solution. These network increases, identified in orange in the figures, do not constitute an alternative grid solution, as they do not all belong to the same solution. Adding one of these increases to the SEW-based needs would deliver very close benefits to those delivered by addressing the SEW-based needs alone.

In particular, considering the sensitivity of the analysis on the cost estimates used for the optimisation process, these possibilities must be considered in order to not misdirect the sound development of the necessary solutions to the needs. This is especially important in the subsequent steps where further analyses in terms of environmental impact, viability, benefits beyond SEW and refined costs are carried out in order to complement the identified needs.

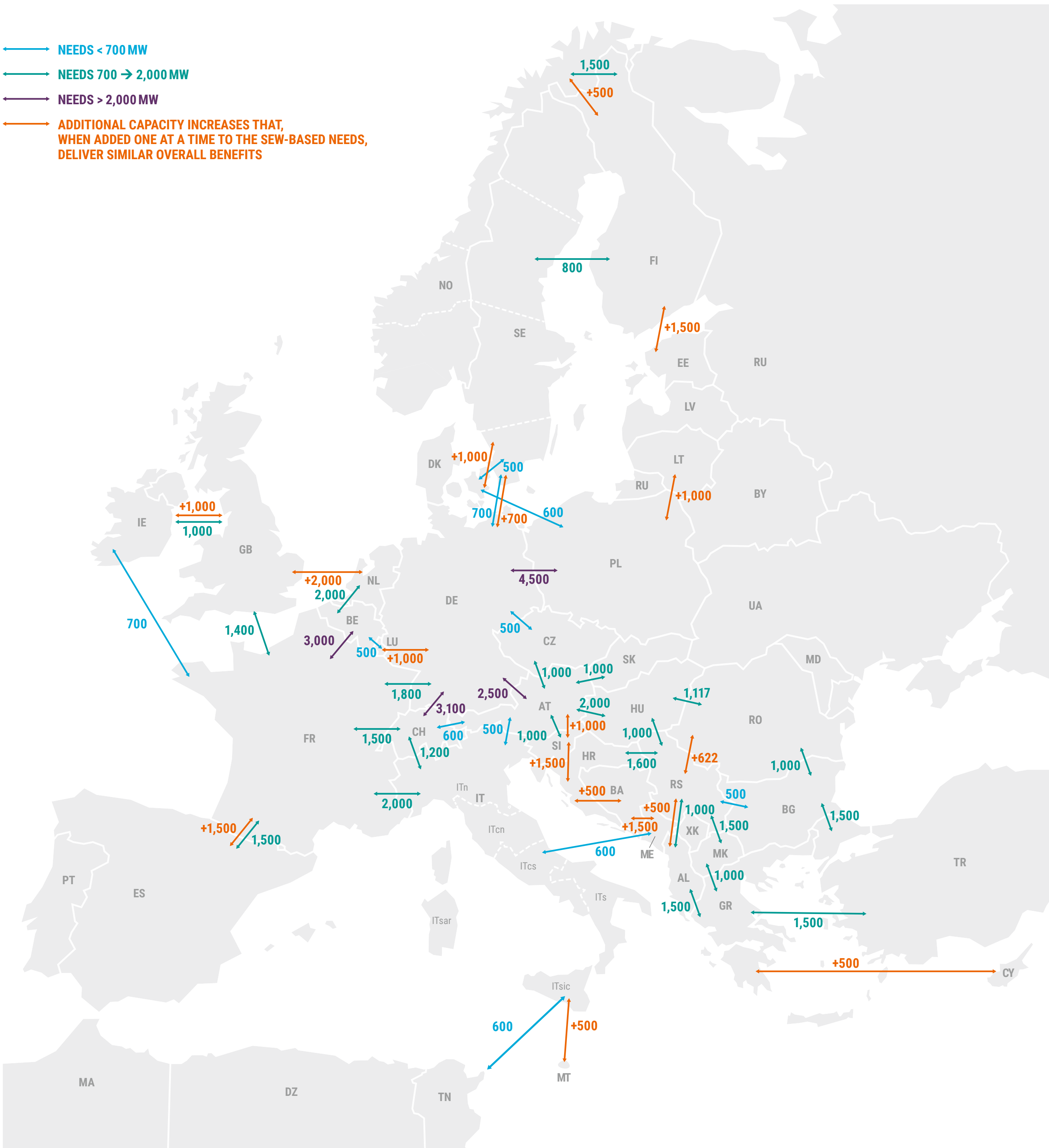


Figure 1.4 – Needs for capacity increases identified in the 2030 horizon, additional to the 2025 network (SEW-based Needs 2030) and additional network increases included in grid solutions that were only slightly more expensive than the SEW-based Needs 2030.

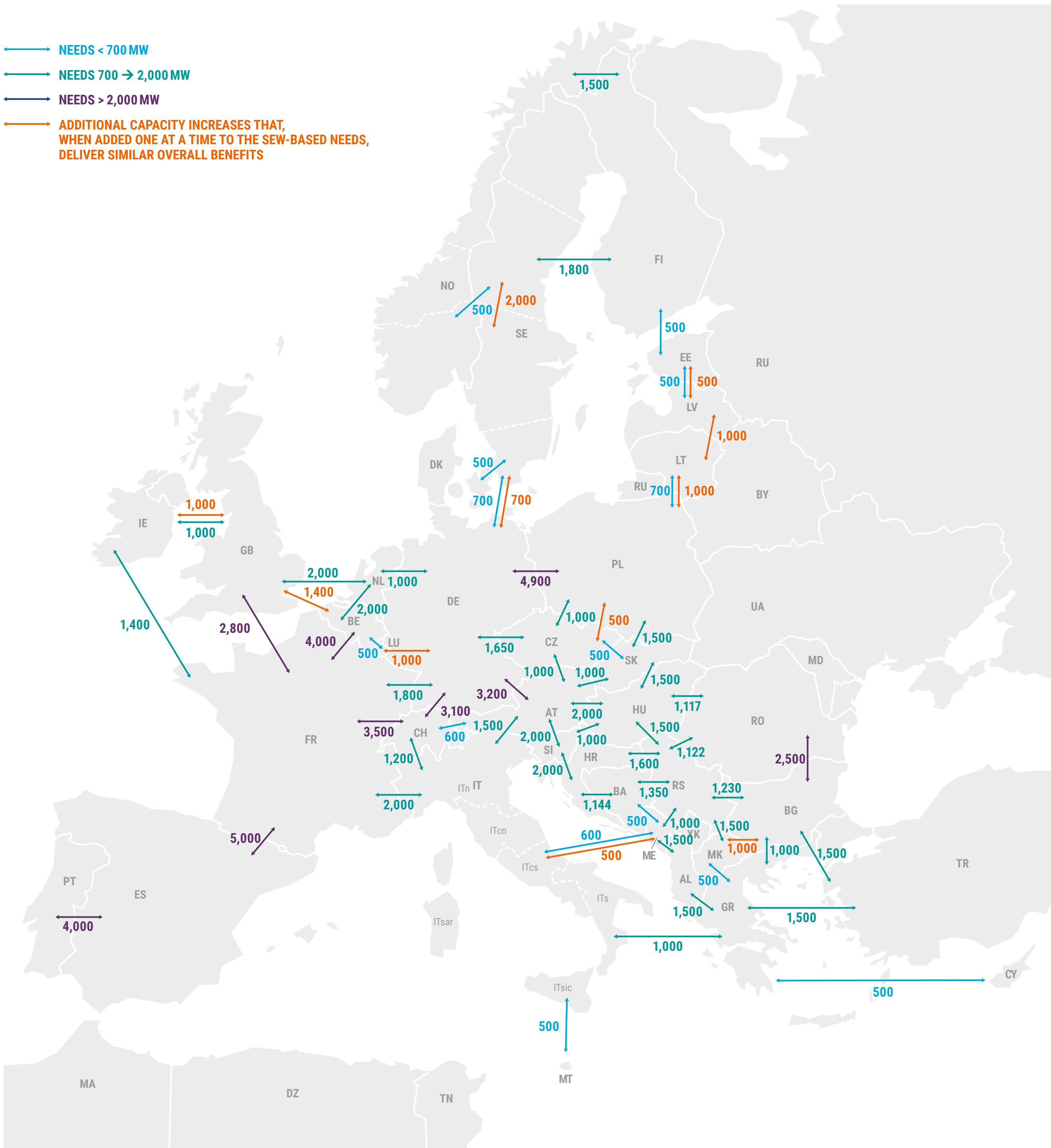


Figure 1.5 – Needs for capacity increases identified in the 2040 horizon, additional to the 2025 network (SEW-based Needs 2040) and additional network increases included in grid solutions that were only slightly more expensive than the SEW-based Needs 2040*.

* The need at the Italy-Tunisia border has been assessed only in the 2030 horizon because of methodological limitations. As a result, the absence of any need on IT-TUN in the 2040 horizon is only due to the non-assessment of needs on this border.

What is the impact on the internal grid and how does the internal grid affect network expansion?

Reaching the level of cross-border exchanges that result from the needs identified in the SEW-based Needs and rely on the National Trends scenario for 2030 and 2040, will create new needs for reinforcement of internal networks in the European national grids. Therefore, national TSOs will need to analyse the situation of internal grids in the national framework as well as in the European framework, to ensure that internal grids accommodate future flows and are fit-for-purpose in the energy transition.

The rise of offshore wind and offshore grid infrastructure development

Europe has today 22.1 GW of offshore wind capacity, corresponding to 5,407 grid connected wind turbines across 12 countries[1]. The resource potential for offshore wind in Europe in several areas is very high. Furthermore, the cost of offshore wind has declined substantially in the last decade, making it an attractive contributor to the European Green Deal. In fact, the National Trends scenario expects reaching 78 and 131 GW in 2030 and 2040 respectively, while the European Commission **Roadmap on Offshore renewable energy strategy** anticipates over 250 GW of installed offshore wind in 2050.

Offshore transmission infrastructure and related onshore connections and reinforcements need to be built much faster than the current onshore grids, which were developed step by step for more than a century. Several challenges for this expansion will have to be addressed in the coming years, including a holistic planning and coordinated on-and-offshore grid developments, combining the fields of grid and spatial planning, engineering, construction and financing. **ENTSO-E's first Position Paper on Offshore Development**, released in May 2020, identifies the basic pillars on successful offshore development supporting offshore wind integration in electricity.

For the System needs study, the wind and solar capacities are part of the scenarios, meaning that connection costs are treated as an externality, which in the case of offshore wind may represent an even higher deviation from overall system costs optimality. The study does not focus on the optimal connection of (all types of) generation, as this is not part of the current ENTSO-E mandate. For that reason, so called "hybrid projects", i.e. the combination of interconnections and offshore generation units, are not identified with the current System needs methodology.

However, the results of the present System needs study, merged with detailed information of offshore power plants, will allow project promoters to define new potential hybrid projects (yellow areas in Figure 1.6) or adapt existing ones, thus proposing new steps towards future modular offshore grid infrastructure. In particular, hybrid projects could help to decrease the cost of exchange capacity in marine areas (submarine transmission projects tend to be expensive), hence making new capacities cost-effective, which they may not have been by themselves. Indeed, there are still some benefits to be gained by new exchange capacities as the differences in marginal costs on these borders are still high (Figure 1.7).

The benefits delivered by these types of projects with the details of the offshore power plants will be assessed in the cost-benefit analysis process of the TYNDP according to the currently valid CBA methodology.

1 WindEurope: "**Offshore wind in Europe**" – key trends and statistics 2019, Feb 2020

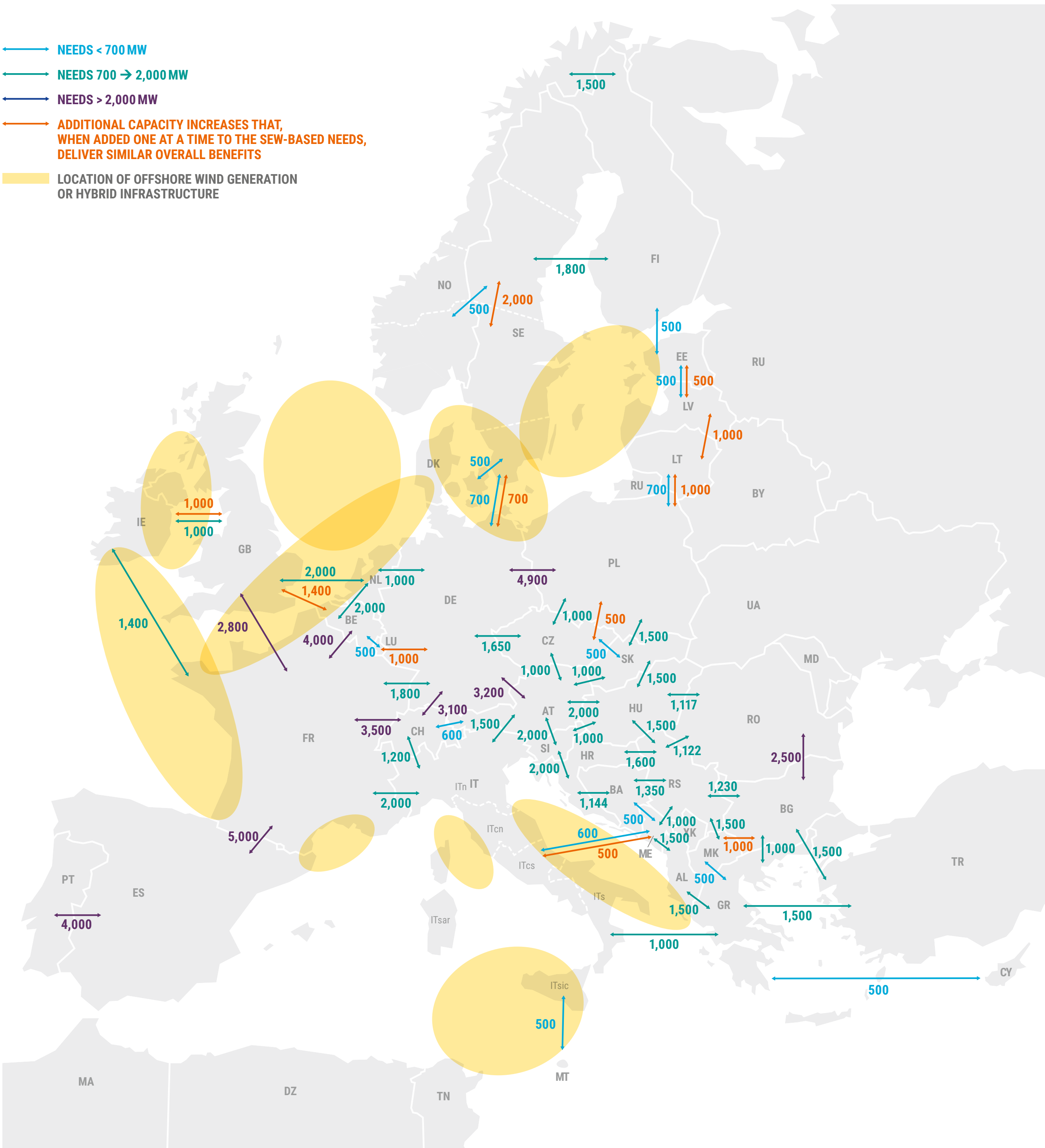


Figure 1.6 – Location of potential hybrid offshore infrastructure (interconnection and generation) and needs for capacity increases identified for the 2040 horizon (SEW-based Needs 2040)

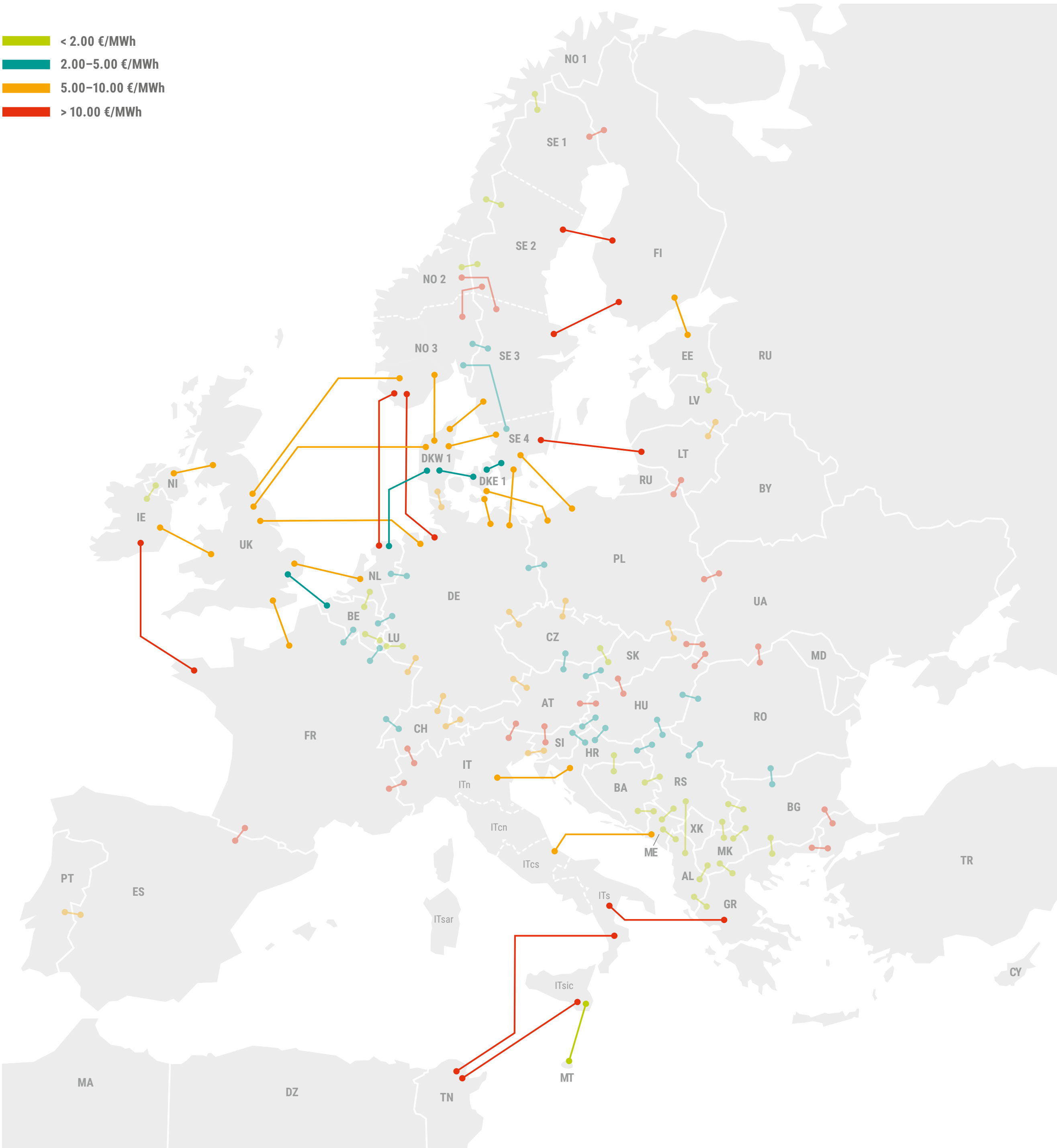


Figure 1.7 – Difference in marginal costs between neighbouring bidding zones in potential locations of hybrid offshore infrastructure (SEW-based Needs 2040) (For the spread in marginal cost in all potential futures for 2030 and 2040, see Chapter 2.2)

The complexity of the offshore system requires a combination of various technical solutions and designs in order to ensure overall system efficiency. In anticipation of the integration of significant offshore generation capacities, ENTSO-E is looking into methodologies for identifying potential hybrid project needs in future TYNDPs. Future TYNDPs will analyse the offshore grid infrastructure further based on the advancement of national and regional development plans.

2 How addressing system needs benefits Europe

In this chapter we compare the SEW-based needs presented in Chapter 1 to a hypothetical future where there would not be any further increase in transmission capacity after 2025. This comparison highlights the benefits delivered by increased network capacity on a range of indicators, in terms of reduced curtailed energy, reduced CO_2 emissions, reduced price divergence between neighbouring countries … Addressing system needs will be key for Europe to preserve security of electricity supply, deliver the Internal Energy Market and make the Green Deal a reality.

Enabling Europe to realise the Green Deal

110 TWh of curtailed energy saved each year by 2040

Increasing the exchange capacity in Europe helps the integration of renewable energy by offering more opportunities to RES power plants to be used. Indeed, without network reinforcements after 2025, the RES generation would be so high at some time in some countries that some energy has to be curtailed: by 2030, 49 TWh/year would be spilled whereas this volume increases to 244 TWh/year by 2040. This represents a share of over 1 % of annual RES generation in 2030 and 5 % in 2040[2].

By taking advantage of the different energy mix over Europe and the different RES peaking period between countries,

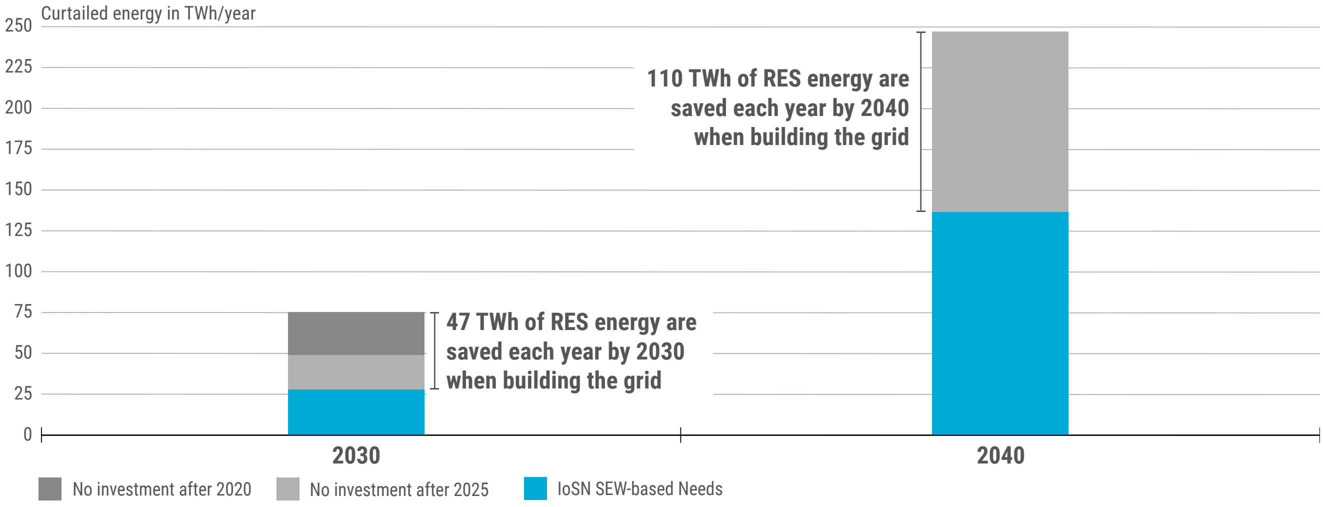


Figure 2.1 – Curtailed energy in TWh/year in the 2030 and 2040 horizons

2 As far as hydrological losses are concerned, curtailed energy values does not include water that is not used because generation turbine capacity is not high enough.

the SEW-based needs decrease drastically the curtailed energy. With the evolution of the energy transition (RES installed capacity in Europe increases by 28 % between 2030 and 2040), this effect increases over time: the reduction is 21 TWh / year in 2030 and reaches 110 TWh / year in 2040. Germany and Spain are the most impacted countries due to their high national share of RES generation.

The impact on RES integration is even more important because, in case Europe stops investing in grid reinforcement, RES promoters would not build their units in the first place knowing they will not be able to sell their generation to foreign markets.

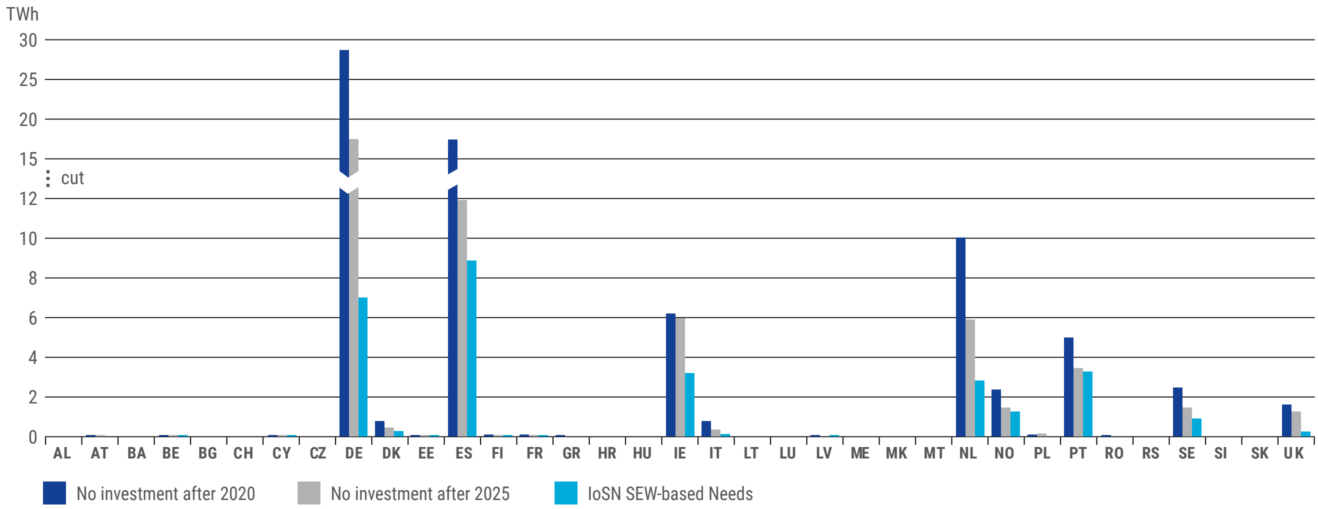


Figure 2.2 – Curtailed energy in TWh in 2030, in No investment after 2020, No investment after 2025 and SEW-based Needs

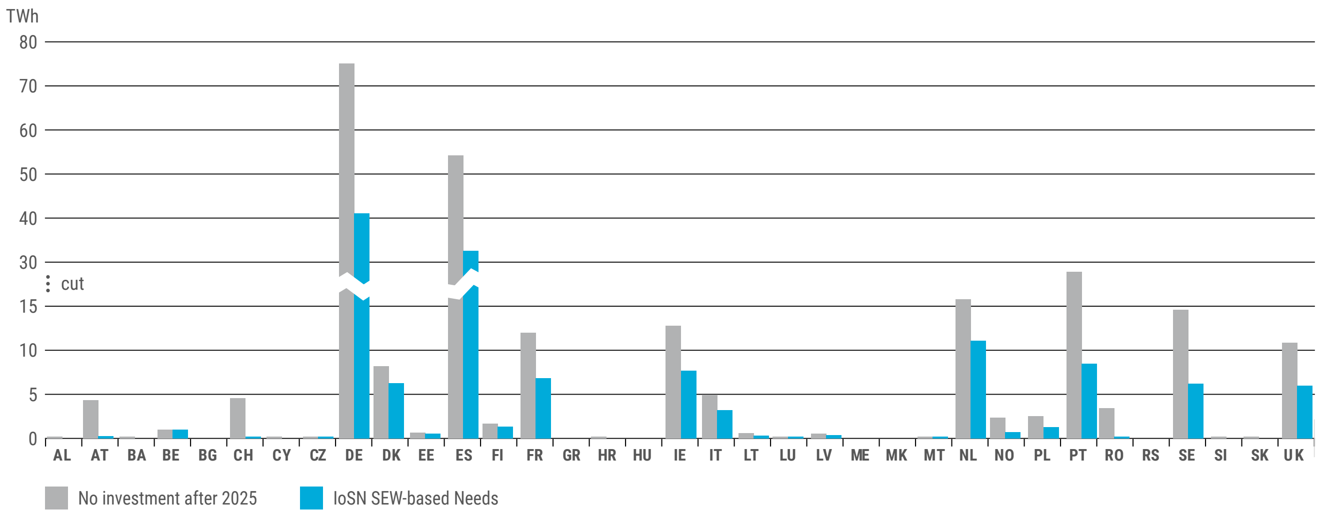


Figure 2.3 – Curtailed energy in TWh/year in 2040, in No investment after 2025 and SEW-based Needs

Over 40 Mton of CO_2 emissions avoided each year by 2030

By allowing a better integration of non-CO_2 emitting generation, increased cross-border network capacity leads to a significant reduction of European CO_2 emissions. This highlights the important role of the network in the path toward carbon neutrality. Compared to a path with no investment after 2025, CO_2 emissions of the power sector decrease by 7 % (40 Mton) per year in 2030 and 12 % (55 Mton) per year in 2040 to reach in Europe 591 Mton /year in 2030 and 391 in 2040[3].

If Europe stopped investing in the grid after 2020, the negative effect would be even larger: by 2030, CO_2 emission would be higher by 60 Mton / year compared to the SEW-based Needs.

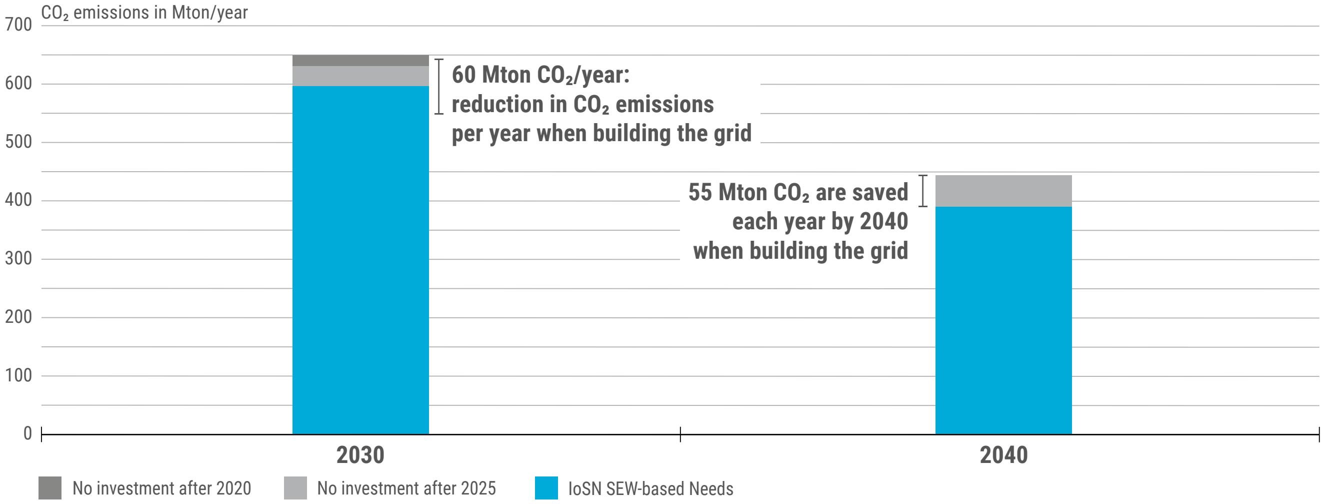


Figure 2.4 – Yearly CO_2 emissions from the power sector in the 2030 and 2040 horizons

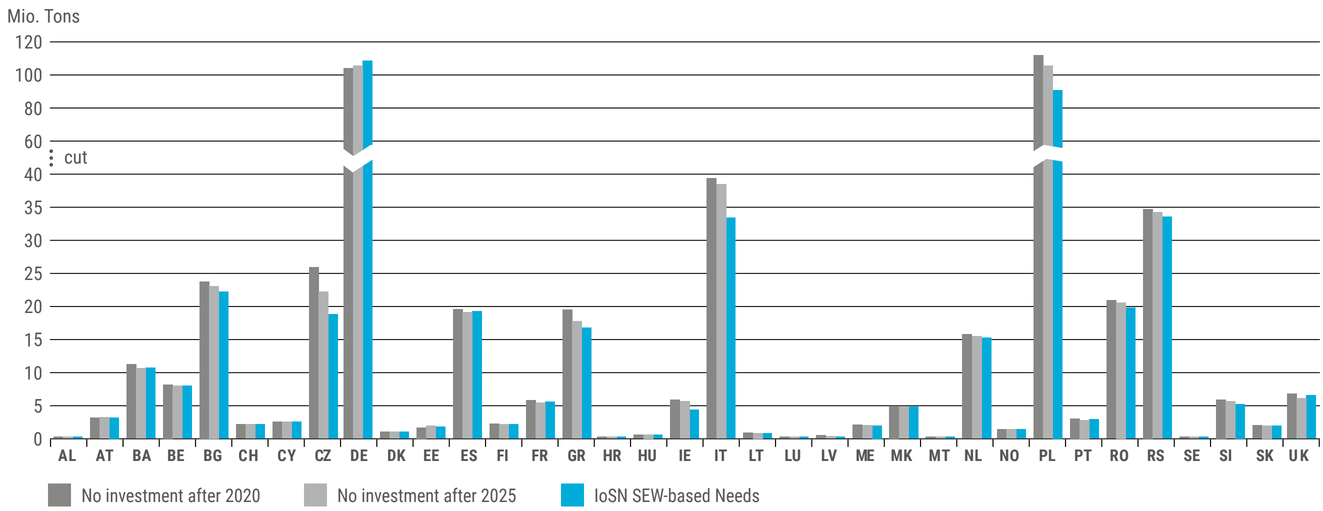


Figure 2.5 – CO_2 emissions in 2030, in 'No investment after 2020', 'No investment after 2025' and SEW-based Needs 2030

3 The overall European emission decreases between 2030 per country and 2040 because of the highest share of renewable energy in 2040 associated with an increase in the ETS CO_2 cost considered at this horizon.

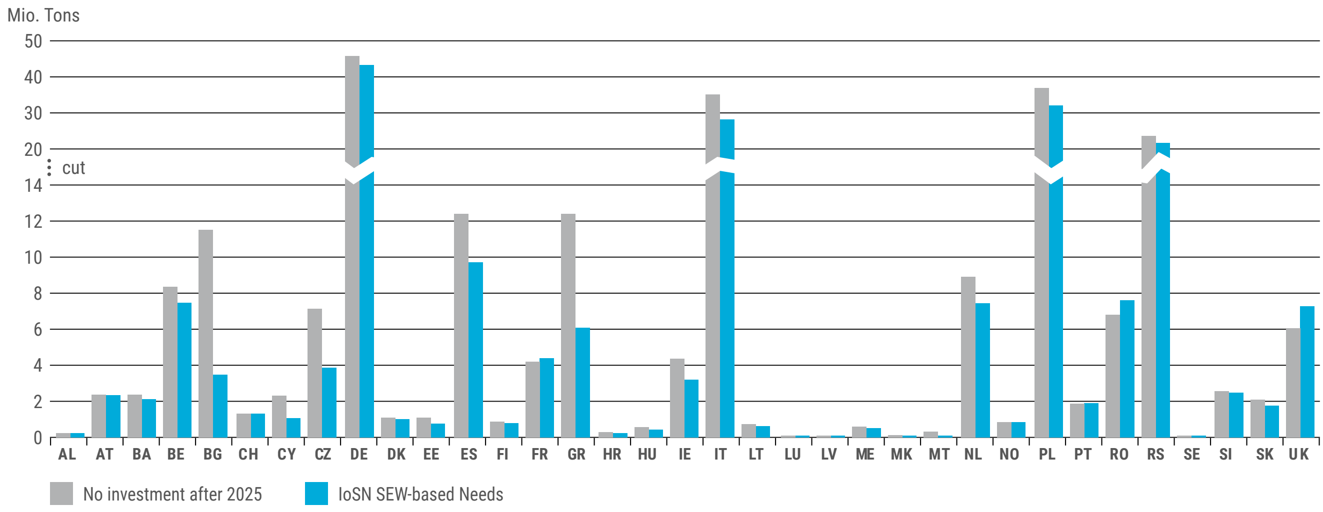


Figure 2.6 – CO_2 emissions in 2040 per country, in the SEW-based Needs 2040 and in 'No investment after 2025'

Because the current identification of system needs methodology focuses on benefits in terms of socio-economic welfare and integration of renewable energy sources, the network increases composing the SEW-based Needs are not optimal with regard to CO_2 emissions reduction. CO_2 is partially taken into account in socio-economic welfare via the ETS CO_2 price which producers have to pay when they emit CO_2, because it is included in the generation cost. However, the ETS CO_2 prices of 28 EUR/ton of CO_2 in 2030 and 75 EUR/ton in 2040 are not sufficient to properly decrease CO_2 emissions to an extent consistent with EU climate ambitions. This explains the relatively reduced impact of the SEW-based Needs especially in the first decade to come, compared to a future with no investment after 2025, when using the current ETS CO_2 price.

To investigate the impact if the CO_2 price was increased, ENTSO-E has run a sensitivity study for 2030 with a price of 100 €/ton of CO_2[4].

	'No investment after 2025' with the current ETS CO_2 price of 28 €/ton	SEW-based Needs 2030 with the current ETS CO_2 price of 28 €/ton	'No investment after 2025' with a CO_2 price of 100 €/ton	SEW-based Needs 2030 with a CO_2 price of 100 €/ton
Increased capacity in GW	–	50	–	74
Curtailed energy in TWh/year	49	28	49	23
CO_2 emissions in Mton/year	630	591	527	477

Figure 2.7 – Key indicators in 2030 in No investment after 2025 and SEW-based Needs, with a CO_2 price of 28 €/ton and 100 €/ton

By increasing the marginal cost of electricity generation for highly emitting plants, increasing CO_2 price changes the merit order in the 2025 starting grid, with plants with high CO_2 emissions being substituted by plants with lower CO_2 emissions. As a result, CO_2 emissions in the 'No investment after 2025' case with a higher CO_2 price would already be reduced by 122 Mton/year.

In a second step, a higher CO_2 price implies a higher level of investment in cross-border network capacity until 2030, with an additional 24 GW of capacity increase (compared to the increase with a lower CO_2 price). These investments in turn decrease CO_2 emissions even more, by reducing curtailed energy by an additional 5 TWh/year.

4 100€/ton corresponds to the central climate change avoidance cost at this horizon according to DG MOVE Handbook on external costs of Transport (2019)

Towards increased market integration

By connecting more consumers with more producers, grid development allows a better use of the cheapest generation. As a result, European countries can exchange electricity to replace expensive generation with cheaper one. On the opposite, limiting exchange capacity alters market integration and would result in splits between regional market prices. Fragmented markets therefore lead to artificially high marginal costs in some countries, with direct impact on consumers' electricity bills. If Europe stops to invest in grid after 2025, exchanges would be constrained leading to an average marginal cost difference[5] of 7 €/MWh between bidding zones by 2030. The impact is even stronger by 2040 with an average marginal cost difference of 35 €/MWh.

Generation costs decrease by 10 billion euro per year by 2040

The capacity increases found in the SEW-based Needs have a major impact on generation costs: they lead to a reduction of costs for Europeans of about 3 bn €/year in 2030 and 10 bn €/year in 2040. These gains far outweigh the cost of building the grid, of 17 bn € for the SEW-based Needs 2030 and 45 bn € for 2040. They are the result of a better use of the European generation mix:

- In 2030, the main drivers of the investments are the better access to RES generation (mainly in Germany, Spain and the Netherlands) and nuclear generation (mainly in France) that replaces expensive thermal generation (in particular gas in Italy and Poland and coal in Poland).

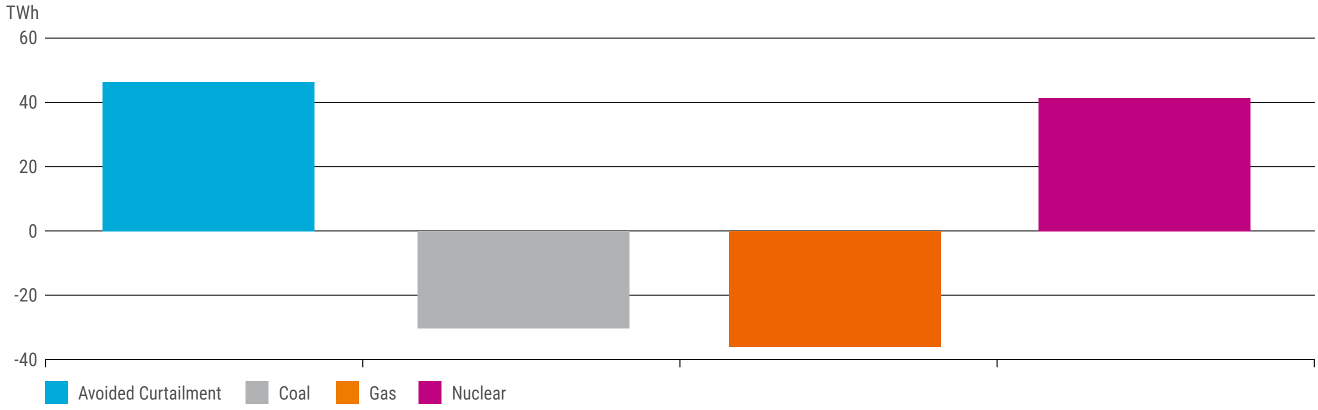


Figure 2.8 – Difference in the generation mix of the ENTSO-E area in 2030, between the 'No investment after 2020' case and the SEW-based Needs 2030 (in TWh)

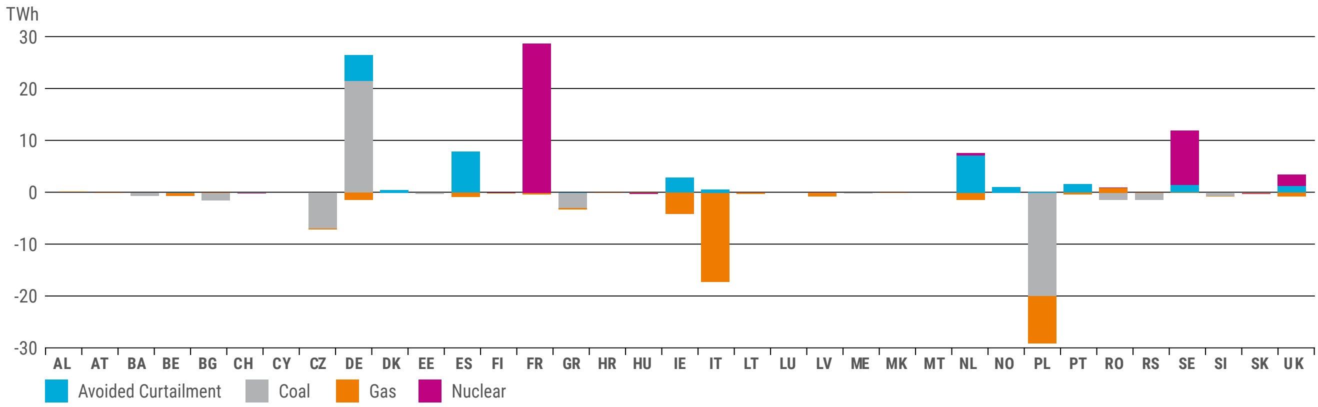


Figure 2.9 – Difference in the generation mix per country in 2030, between the 'No investment after 2020' case and the SEW-based Needs 2030 (in TWh)

5 The price differences discussed here are taken in absolute value (the yearly mean is the mean of the absolute value of the hourly spread) in order to give some insight on the interest of the exchange.

› In 2040, the main driver remains better access to RES generation, with the highest avoided curtailed energy in Germany, Spain, Portugal and Sweden, that replaces thermal generation from gas mainly in Italy, Greece and Poland.

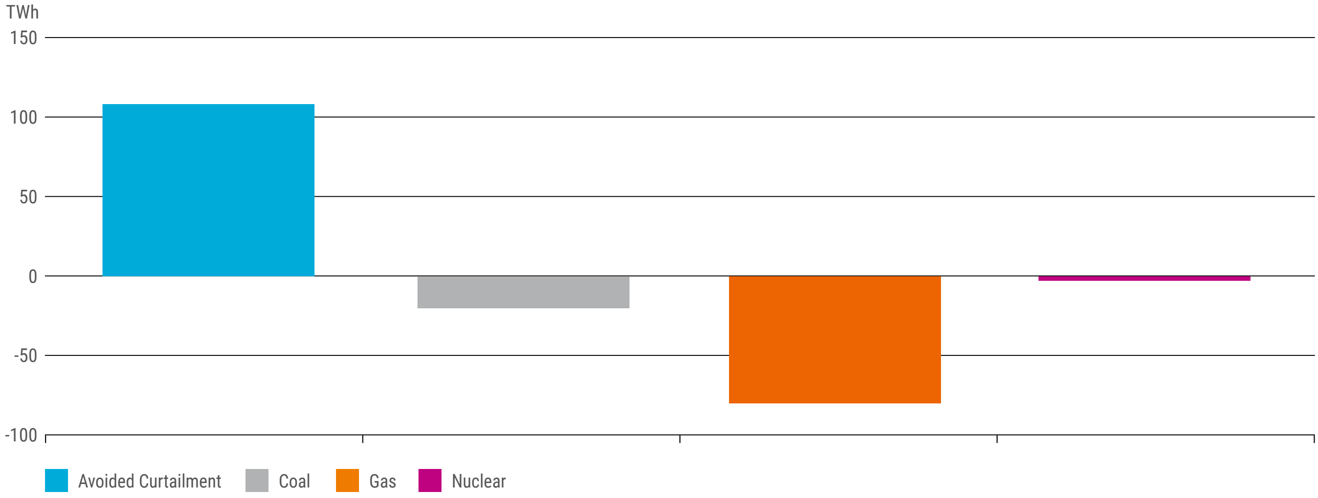


Figure 2.10 – Difference in the generation mix of the ENTSO-E area in 2040, between the 'No investment after 2025' case and the SEW-based Needs 2040 (in TWh)

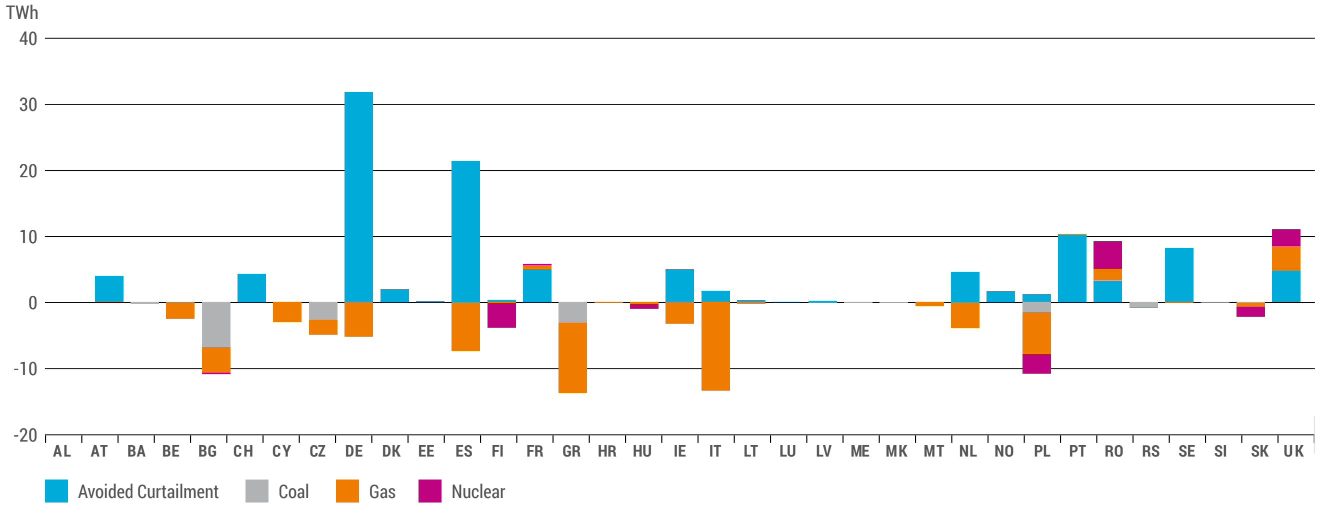


Figure 2.11 – Difference in the generation mix per country in 2040, between the 'No investment after 2025' case and the SEW-based Needs 2040 (in TWh)

Higher electricity exchanges and price convergence between countries

Cross-border capacities increases allow European countries to exchange more energy: in total an additional 256 TWh / year and 467 TWh / year would be exchanged in 2030 and 2040 respectively, relative to the situation where Europe would not invest in the grid after 2025. This brings the total exchange volume to 909 TWh / year in 2030 and 1,176 TWh / year in 2040.

In addition, increasing cross-border capacities converges European marginal costs[6] to an average spread under 4 € / MWh and 8 € / MWh in 2030 and 2040 respectively. For example, with no grid investments after 2025, the French-Italian border would be congested 95 % of the time in 2030 with an average price difference of 24 € / MWh. The SEW-based Needs reduce

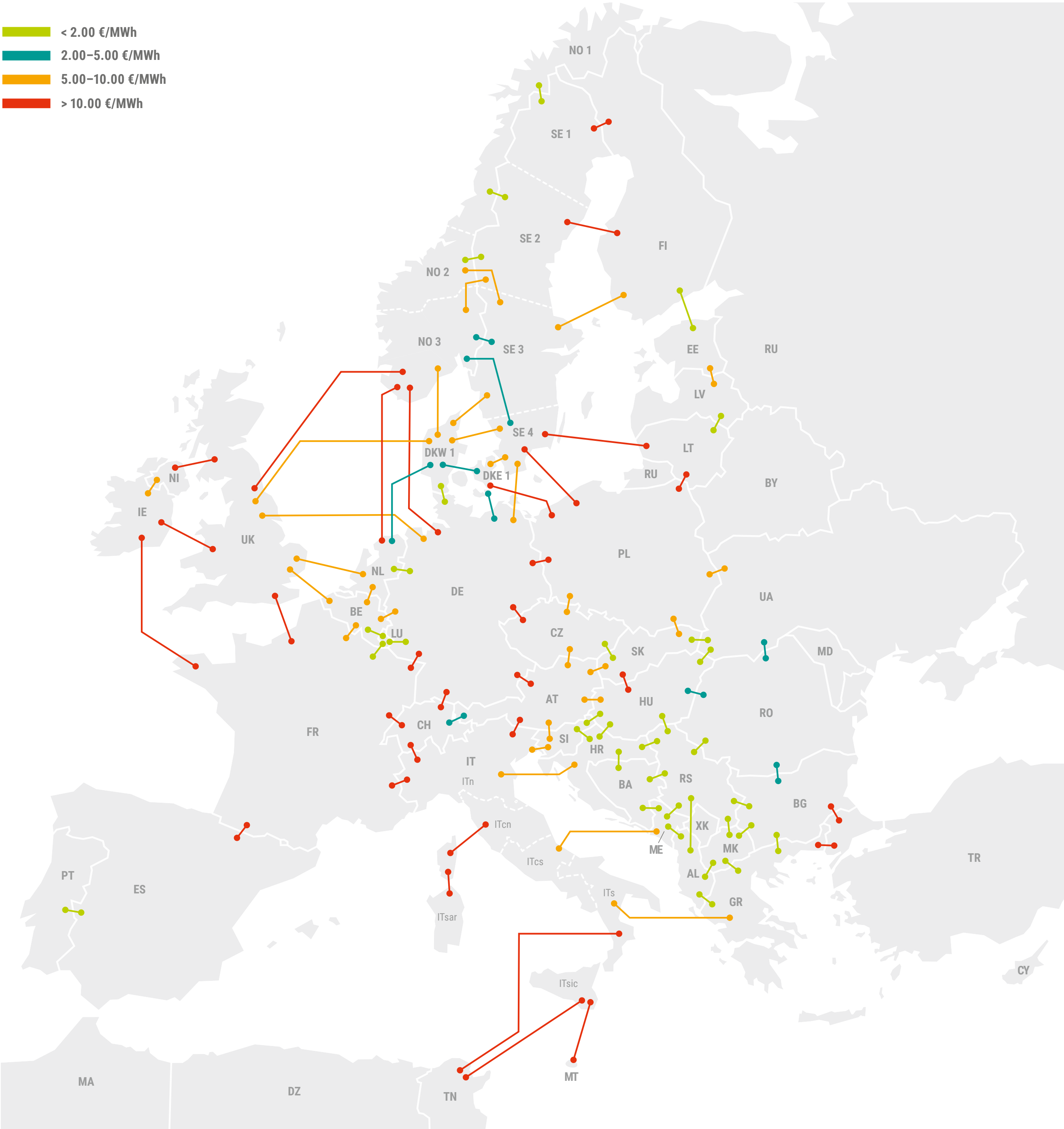
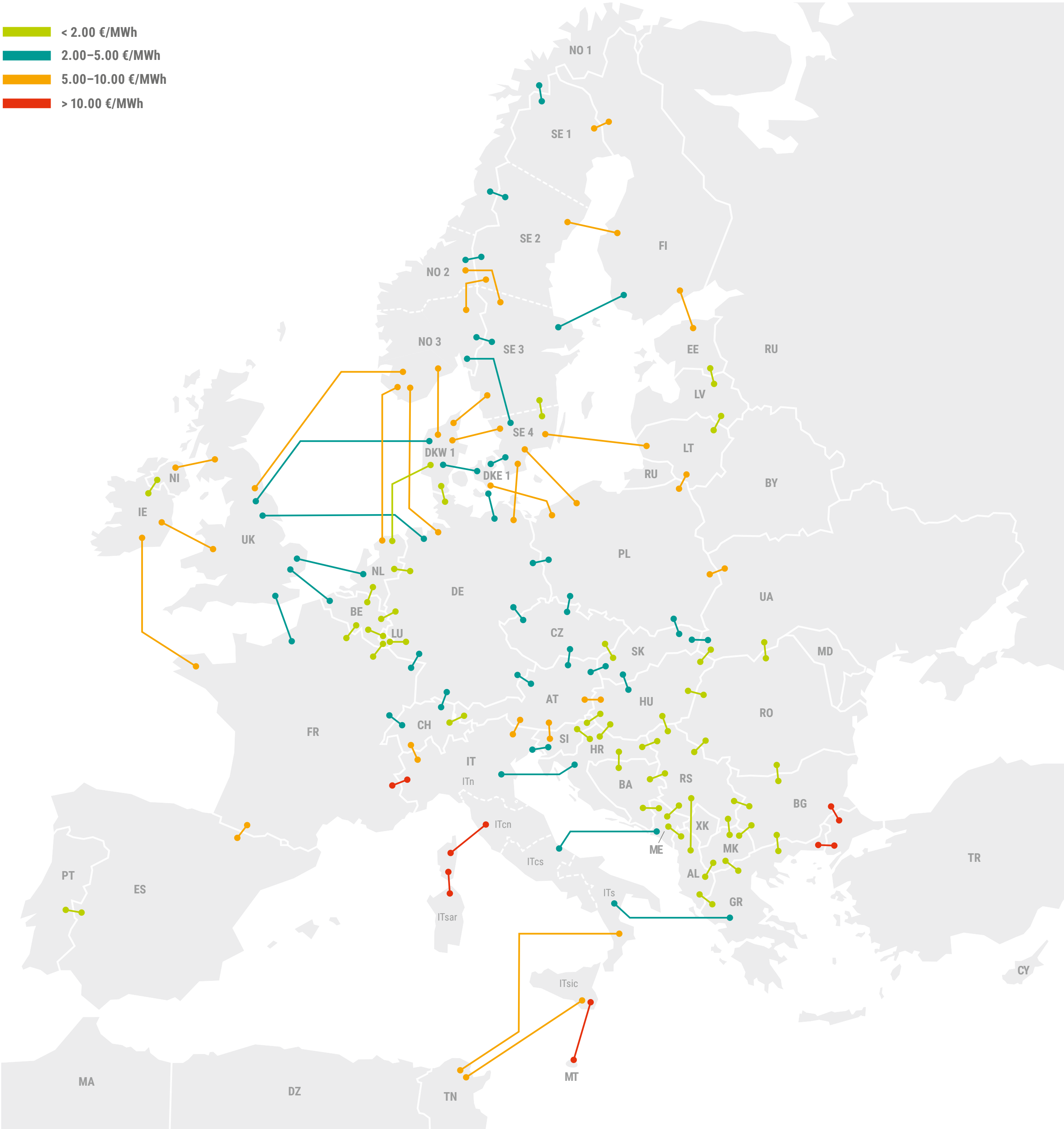


Figure 2.12 – Difference in marginal costs between neighbouring bidding zones in 2030, in 'No investment after 2020' case (left) and the SEW-based Needs 2030 (right)

6 Countries with high marginal costs tend to see these costs decrease and countries with low marginal costs tend to see an increase.

annual congestion to 85 % and reduce the average annual price difference by 13 € / MWh, to an absolute value of 11€/MWh. By 2040, without any investment after 2025 the French-Italian border could face an average marginal cost difference close to 41 € / MWh. With investment, this price difference would decrease by 52 % bringing it close to 19 € / MWh.

Nevertheless, zeroing electricity market differences between neighbouring countries is not an objective in itself, as local conditions and grid development costs must be taken into account.



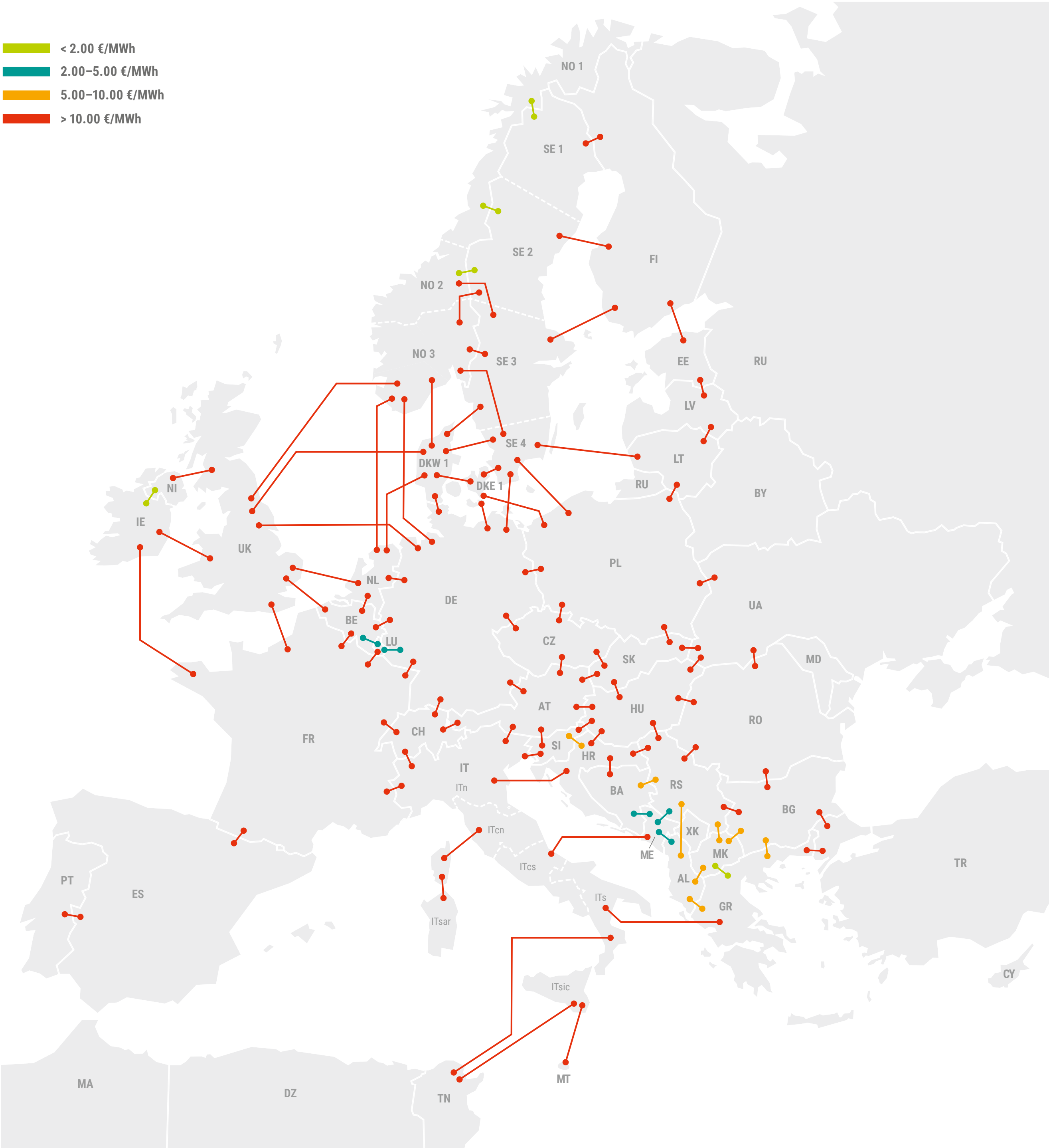
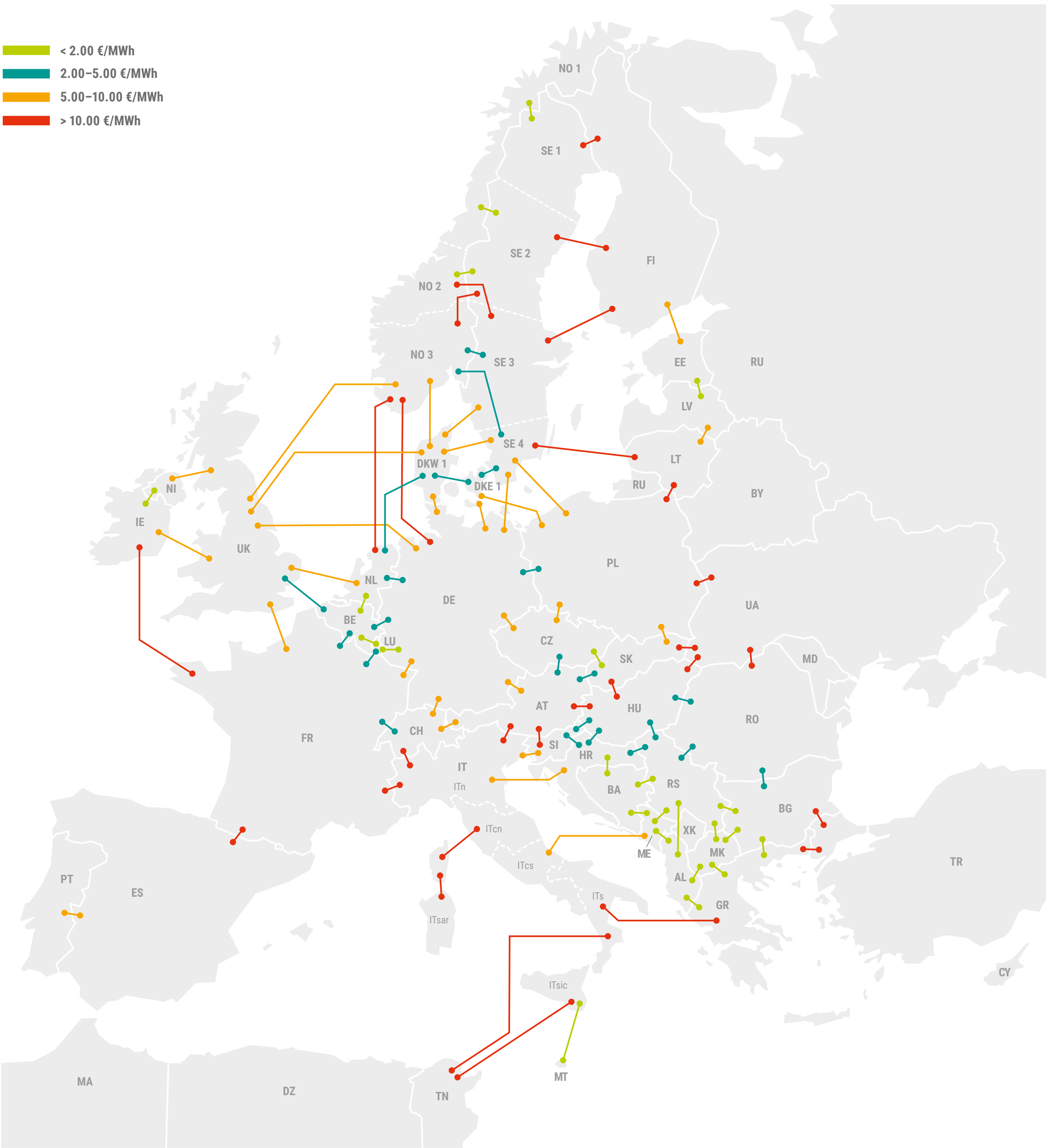


Figure 2.13 – Difference in marginal costs between neighbouring bidding zones in 2040, in 'No investment after 2025' (left) and in the SEW-based Needs 2040 (right)


< 2.00 €/MWh
2.00–5.00 €/MWh
5.00–10.00 €/MWh
> 10.00 €/MWh
NO 1
SE 1
SE 2
FI
NO 2
NO 3
SE 3
EE
RU
LV
SE 4
DKW 1
DKE 1
LT
RU
BY
NI
IE
UK
NL
PL
DE
UA
BE
LU
CZ
SK
MD
AT
HU
RO
CH
FR
SI
HR
IT
ITn
BA
RS
BG
ITcn
XK
ME
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Preserving reliable access to electricity

Connecting generation and demand in a reliable manner at reasonable costs is one of the main tasks of TSOs. Exchange capacities play an important role in this task as they allow countries to help each other during stressed periods of time (for example a cold wave or a low wind generation period).

As a consequence, no investment beyond 2025 would have a tangible impact on Europeans' economy and quality of life by putting at risk the reliability of access to the electricity infrastructure. If renewable energy sources and new electricity uses keep developing as foreseen, failure to deliver on transmission investments could lead to unacceptable levels of load shedding, meaning that the final demand could not be supplied at some time. This could result in damaging business operability. In order to avoid these consequences, some additional generation would have to be built leading to higher costs for European consumers.

In addition to this mutual support in case of extreme situations, daily management and reserve sharing would not be possible at the required level by the 2030 and 2040 scenarios.

The current System needs study did not focus on analyzing energy-not-served, meaning the amount of final demand that cannot be supplied within a region due to a deficiency of generation or interconnector capacity. Studying energy-not-served requires complex and time-consuming analysis with multiple climate years to obtain reliable values. However, the contribution of projects composing the TYNDP 2020 portfolio to security of supply will be assessed in the cost-benefit analysis performed for each project, to be released in November 2020.

In addition, the new European Resource Adequacy Assessment (ERAA) substituting the former Mid Term Adequacy Forecast (MAF) will address this topic in detail. The first ERAA release will be published in 2021 and will analyze up to the 2030 horizon.

3 What if there was no physical constraint in the grid?

Chapter 2 investigated a future where the transmission grid would be very constrained with the No investment after 2025 and 2020 cases. The present Chapter looks at the opposite situation: what would happen if there was zero limitation to transmitting electricity across Europe? In the following figures there is unlimited available transmission capacity between countries. This situation is called ‘copperplate’.

It is important to stress that this is an entirely theoretical exercise. In no possible future could all grid constraints ever be removed, because the copperplate ignores network capacity limitations and relies on infinite economic support. However, the value of the copperplate exercise is to reveal the maximum benefits that could be captured by reinforcing the grid. When compared to the situation where Europe would stop investing in the grid after 2025 presented in the previous Chapter, the copperplate indicates the absolute maximum benefits that – in a very theoretical case – could be captured by unlimited increased cross-border network capacity.

In a copperplate situation, by 2030 Europe would save 5.4 bn €/year in the copperplate compared to the No investment after 2025 situation. Curtailed energy would be reduced by 47 TWh/year and CO_2 emissions would be cut by 76 Mton/year. By 2040 system cost savings would reach 13.7 bn euro/year, with 191 TWh of avoided curtailed energy and 75 Mton/year of saved CO_2 emissions.

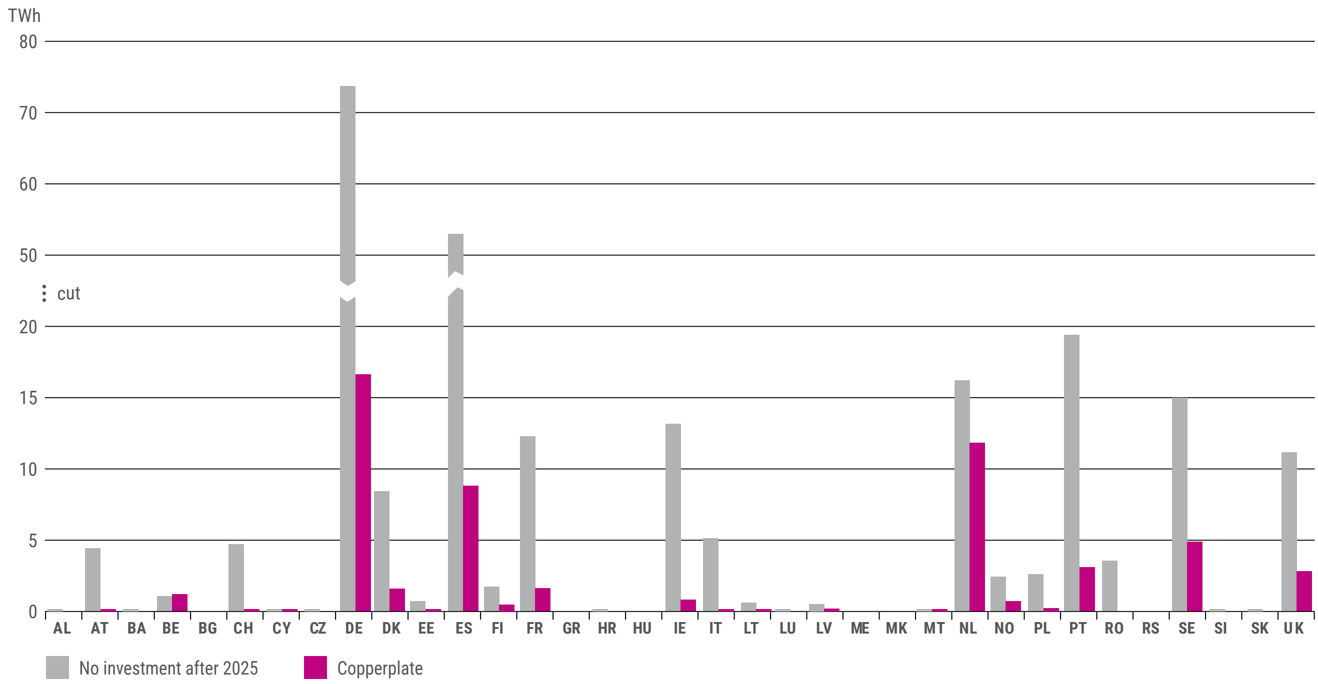


Figure 3.1 – Curtailed energy in TWh in ‘No investment after 2025’ and Copperplate 2040

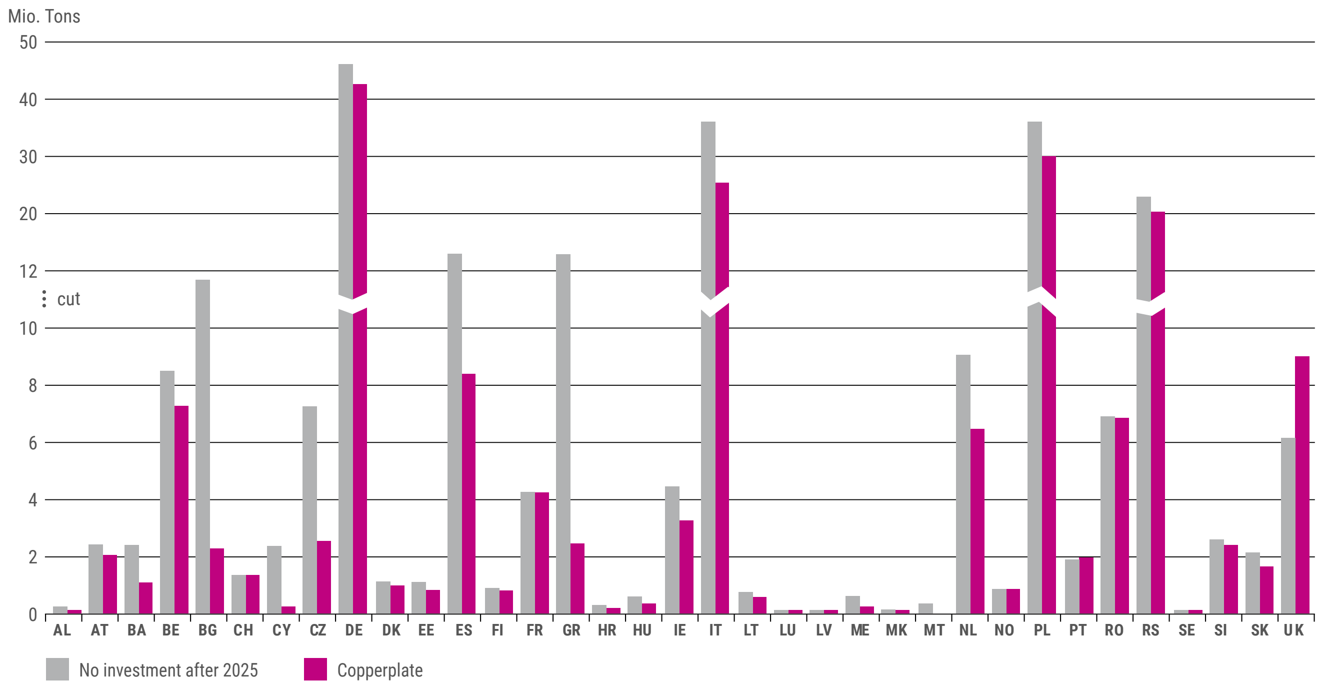


Figure 3.2 – CO_2 emissions in Million tons in 'No investment after 2025' and Copperplate 2040

The SEW-based Needs can deliver about 70% of the maximum achievable benefits

The copperplate analysis delivers the most insights when compared to the benefits delivered by potential network increases. To that end, the next figures compare the copperplate with the IoSN SEW grid. For both the 2030 and 2040 horizons, the IoSN SEW grid catches a share of the maximum benefits of the copperplate of about two thirds or 70%, depending on the indicator. Put differently, this means that the combination of potential network increases that optimizes system costs up until 2040 would deliver about two thirds of all benefits that can possibly be captured.

It is important to remember that the 'No investment after 2025' grid includes projects that will commission between today and 2025. Benefits delivered by these projects, that are currently either under construction or in the permitting phase, are not considered in the 70%. Therefore, the real share of benefits captured by network increases that are either currently under construction, in permitting phase, planned or only conceptual is higher than 70%.

The maximum reduction in CO_2 emissions reaches 75 Mton / year in the copperplate in 2040 compared to the situation with no investment after 2025, of which the SEW-based Needs capture 55 Mton / year, so about 70%. These numbers must be considered while keeping in mind that the System needs methodology is focusing on optimizing generation and transmission costs and is not fit to capture all potential CO_2 emissions reductions (as explained in Section 2.1).

The remaining CO_2 emissions in the copperplate, 552 Mton / year in 2030 and 371 Mton / year in 2040, are inherent to the scenario National Trend. If the scenario being investigated foresaw higher levels of RES, such as scenario Distributed Energy, remaining CO_2 emissions in the copperplate would be lower.

In the 2040 horizon, the SEW-based Needs capture 110 TWh / year of the maximum possible saved curtailed energy of 191 TWh / year, about 57%.

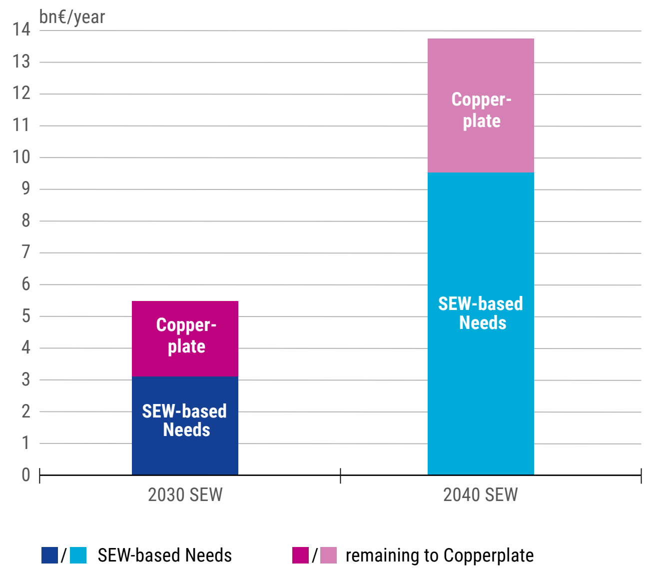


Figure 3.3 – Share of the maximum possible increase in socio-economic welfare (copperplate) that is captured by the SEW-based Needs, in 2030 and 2040.

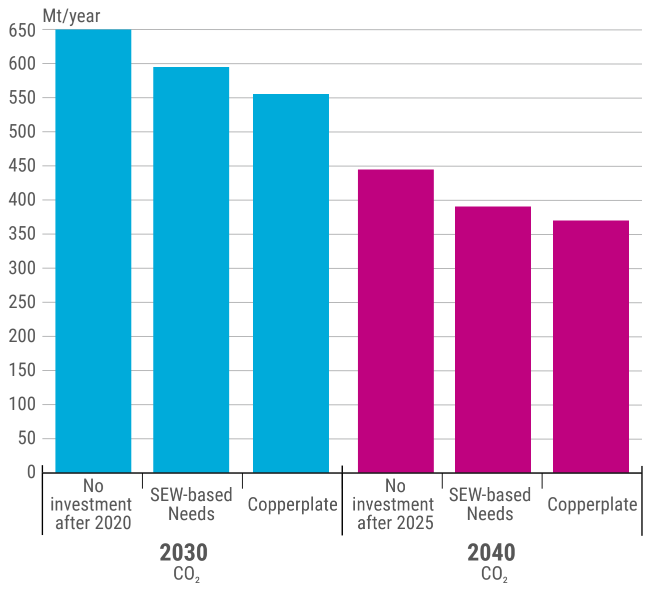


Figure 3.4 – Share of the maximum possible reduction in CO_2 emissions from power generation (copperplate) that is captured by the SEW-based Needs, in 2030 and 2040.

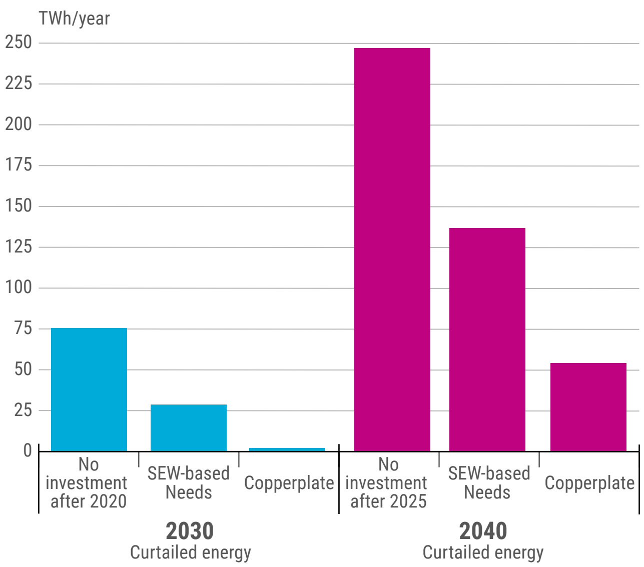


Figure 3.5 – Share of the maximum possible reduction in curtailed energy (copperplate) that is captured by the SEW-based Needs, in 2030 and 2040.

Why is there still curtailed energy in the copperplate?

Even in a world without physical constraints for the grid there would still be curtailed energy. This is due in part to non-dispatchable generation from renewable energy sources, as wind and solar will sometimes be higher than the load on windy and/or sunny days. In addition, some non-RES power plants cannot be turned on and off every hour.

How to increase the benefits captured?

As visible in the previous figures, the SEW-based Needs do not capture the entirety of the maximum achievable benefits. In 2040, 4.2 billion euro/year in system costs savings, 21 Mton/year of avoided CO_2 emissions and 81 TWh/year of saved curtailed energy are left to be captured. Several solutions may lead to increasing the captured benefits beyond the SEW-based Needs.

There is room for other technologies than transmission

The interplay between other technologies, such as storage or power-to-gas and transmission, could play a role to improve the share of the maximum benefits captured by the SEW-based Needs. In addition, non-transmission technologies could deliver benefits not included in the copperplate. Because the System needs methodology is based on cross-border capacity increases, it does not capture entirely the potential benefits of non-transmission technologies that do not translate into increase of cross-border network capacity. The copperplate must be understood as the maximum potential benefits that could be achieved by increasing cross-border network capacity. Other solutions combined with network increases could take Europe even further.

For example, Figure 3.6 shows the countries with curtailed energy left in the SEW-based needs 2040, representing a total of 81 TWh that could be captured by i.e. storage projects. Another example is that of maritime areas, where the remaining differences in marginal cost between countries in the SEW-based needs case show that there is still benefits to be captured, potentially by hybrid offshore infrastructure (see Chapter 1).

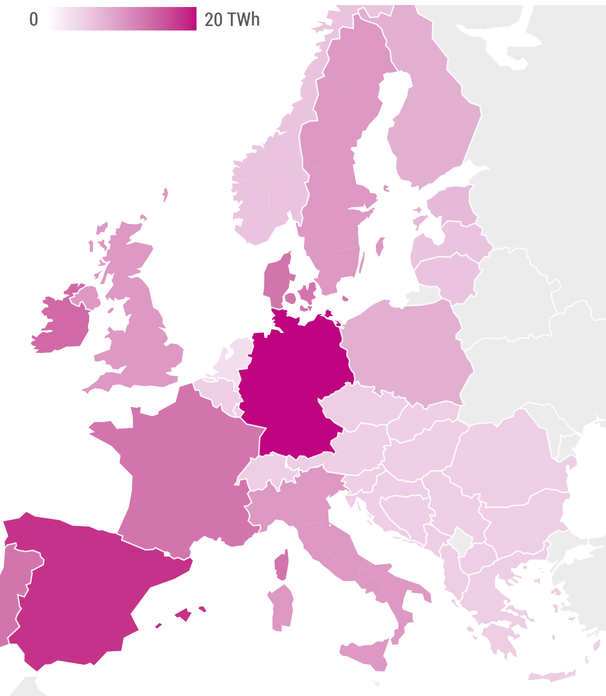


Figure 3.6 – Curtailed energy in TWh in 2040, difference between the curtailed energy avoided in the SEW-based Needs and the curtailed energy left in the Copperplate

Transmission projects with lower costs, a different location, with new technologies or with additional benefits not captured by the current System needs methodology could contribute to capturing part of the remaining benefits

The 2020 System needs methodology is focused on socio-economic welfare and integration of renewable energy sources, so benefits of proposed network increases driven by other considerations, such as CO_2 emissions reduction or security of supply, have not been properly captured. Another limitation is that the current System needs methodology does not identify offshore hybrid projects, i.e. the combination of interconnections and offshore generation. This is due to the fact that identifying optimal generation connection is not among the tasks of the TYNDP. Thus, generation units are generally part of the scenarios and the cost and routing of their connection to the network are not part of the System needs optimisation task.

Most importantly, the benefits delivered by the SEW-based Needs depend on the proposed list of network increases provided to the optimizer (see Methodology Chapter). It is possible that some of the proposed capacity increases were too expensive considering the border at hand and the benefits provided, and were therefore not selected in the SEW-based Needs. It follows that less expensive increases on the same border, maybe with a different technology, may have been included.

Finally, on some borders the copperplate is not attained while the remaining price spread between bidding zones is high: this indicates potential for additional network increases that have not yet been thought off by transmission project promoters and were not proposed to the optimisation.

4 How do results of the 2020 system needs study compare with 2018 results

The challenges of the current SEW-based Needs, that is, the capacity increases identified in this 2020 exercise for the 2040 horizon, are significantly higher than the ones identified in the 2018 exercise, both in the NTC and the zonal test approaches.

Compared to the 2018 system needs exercise, the 2020 exercise for the 2040 horizon finds a global increase of 37 additional GW of cross border capacity increases, with individual capacity increases on almost half of the borders (at least additional 1 GW on half of them). The highest increases compared to the 2018 system needs are on the German-Polish border (with additional 5 GW) and on the Spanish-Portuguese border (with additional 2.5 GW). 15 borders see less need for capacity increases that in the 2018 exercise with at least 1 GW less.

The benefits captured by the 2020 SEW-based Needs are also higher in terms of variable generation cost (socioeconomic welfare), avoided CO_2 reduction and avoided curtailment.

Figure 4.1 illustrates the increase or decrease of the cross-border capacity needs for 2040, in MW, between the System needs study of the TYNDP 2018 (realised with an NTC model) and the System needs study 2020 (done with a zonal model). The variation corresponds to the difference in the final NTC values on each border after addition of the identified system needs for both studies[7].

Comparing the results with the same zonal modelling approach, the main reasons for the differences in the results are the scenarios themselves that affect heavily the results, and the reference grid used that in 2017 was based on the 2027 horizon, while in 2020 is based on the 2025 horizon. This difference with a reduced network as the starting point results in higher capacity needs for the 2040 horizon.

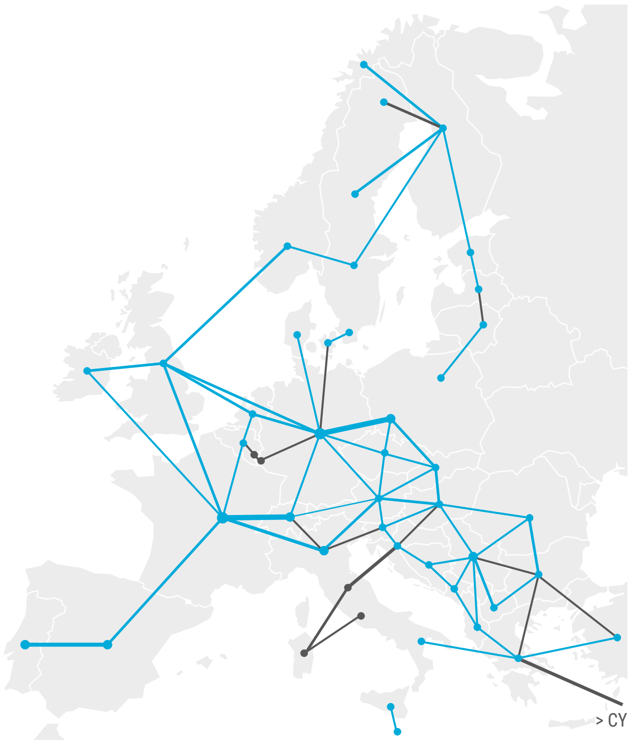


Figure 4.1 – Increases (blue) and decreases (grey) of identified needs in the 2020 System needs study compared to the 2018 System needs study

Although results show some differences, ENTSO-E considers that they are consistent enough, confirm the usefulness of the zonal methodology approach and require continuous evolution, improvement and consistency check in future System needs studies.

7 This is a rough comparison considering that the characteristics of a zonal and NTC modeling are quite different

5 New needs in a new set-up: Challenges for system Operations – Dynamic study results

Based on the TYNDP scenarios, previous editions of the TYNDP System needs study revealed the trends in which the system is evolving: more RES at all voltage levels, more power electronics either in generation or HVDC connections, a very variable mix of generation and also large and highly variable power flows. This combination of trends, observed in all synchronous areas, translates to technical challenges in several aspects such as in frequency, voltage or congestion management control.

Having in mind the ambitious political goals set out in the Clean Energy Package and the European Green Deal, aiming at making Europe climate neutral in 2050, those trends, and its technical challenges, are becoming more and more evident even in areas where the immediate concerns are more mitigated, such as Continental Europe. This is reflected in the present report.

In order to achieve the climate targets adopted by the EU, more and more renewable energy generation plants need to be built. The future system will also need to be operable in real-time by TSOs. The changing environment radically transforms the way this will be done, leading to new technical needs for the system. It must also be noted that the identified needs go beyond the successive incremental steps from the changing environment. It is necessary to shift the perspective into creating today the effective boundary conditions to successfully meet the decarbonisation goals at their full extension.

Some of the needs may be addressed through the specification of capabilities and services that users (generation or demand) are expected to provide as part of their connection. However, additional nationally and regionally defined network reinforcement projects can also be expected as projects to address the specific dynamic stability needs.

The challenges are real for the system's security, during the transition and towards a future decarbonized power system. However, for this future decarbonized power system, there are also available technical solutions with different levels of maturity and to be applied at all voltage levels. Hence, there is a need for strong transmission/distribution coordination, to involve all system users and to maintain an aligned cooperation with research and development.

In the midterm, until these new technical solutions are implemented, it may be necessary to take additional measures (e.g. RES or power flow limitations) to ensure system security. As such, there is a need to work decisively on the target solutions and to make them available when necessary so that the midterm and probably costly limitations does not last too long.

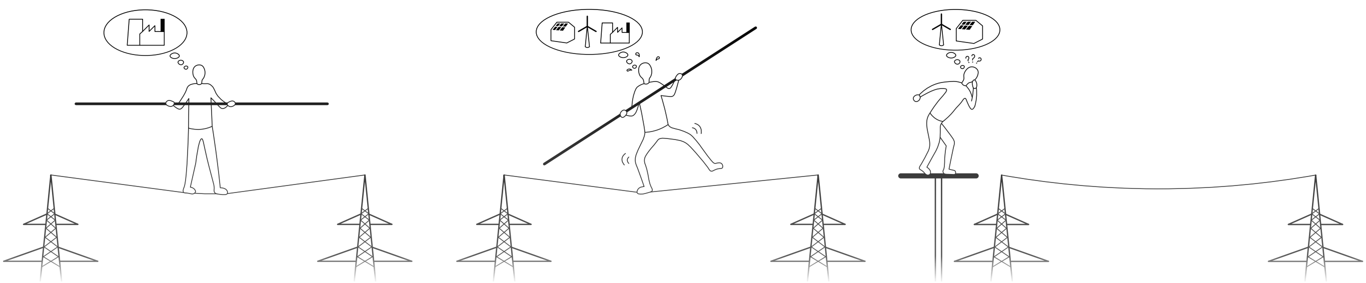
Methodology: Dynamic stability analysis

This chapter looks into the way the system would physically respond to the 2030 and 2040 conditions described in the TYNDP2020 scenarios. The results it presents are based on analysis of the hourly demand and generation profiles, testing operational parameters such as inertia, operational requirements such as flexibility, and availability of ancillary services such as reactive power support, frequency response, and contribution to short circuit current. It is also based on a collection of more local or regional issues identified across Europe. An explanation of the technical concepts presented in these chapters, as well as more detailed results and further analysis is presented in the report 'Dynamic and operational challenges' published alongside this System Needs report.

Frequency management: system inertia and local frequency variations

Frequency variations occur in power systems due to mismatches between active power generation and demand. Once a mismatch takes place, the energy stored in the rotating masses of the synchronous generating units, by virtue of their intrinsic mechanical inertia, provides means of instantaneously balancing any mismatch. The immediate inertial response results in a change in rotor speeds and, consequently, the system frequency. Whereas this does not solve the power mismatch problem in a sustainable manner, it is essential for instantaneously balancing this mismatch until frequency reserve response providers are able to respond to the change of frequency and vary the power output of their plants to restore the balance between generation and demand. Consequently, the level of inertia provides a useful assessment of the system operability emerging challenges.

The following analogy provides a description of the problem having in mind the current trend of more and more synchronous generators being replaced by converter connected generators… now from the perspective of a tightrope walker where the balancing pole provides instantaneous inertia support that allows time for his slower stabilising actions after the tightrope swings …

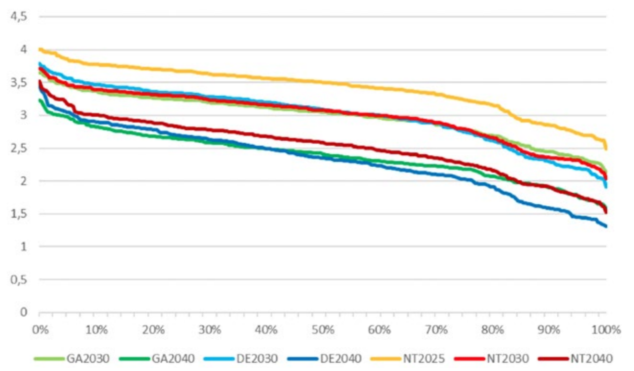


PREVIOUSLY
Inertia of the generators
immediately compensated deviations
(long balancing pole)

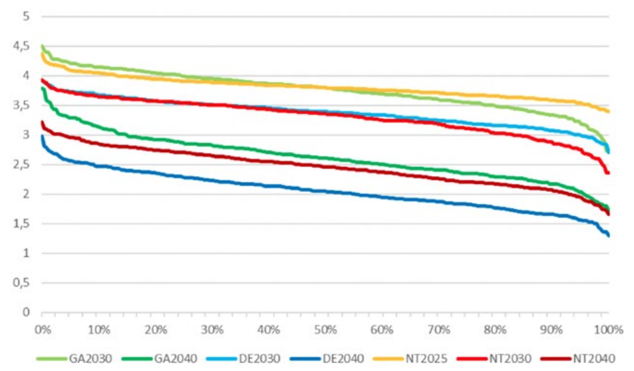
TODAY
the synchronous generators
are less and less often connected to the grid –
Inertia decreases
(balancing pole gets shorter and shorter)

IN THE FUTURE
very low levels of inertia will occur
(wihtout balancing pole)

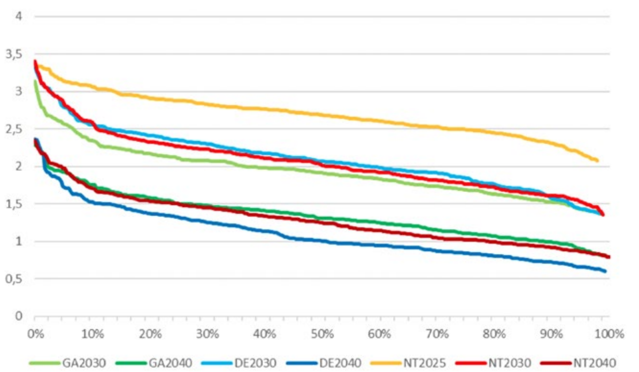
Taking into account the TYNDP 2020 scenarios, the following duration curves present the percentage of hours in a full year where, for all Synchronous Areas, the intrinsic inertia from generators is above any given value within the curve. This estimated equivalent system inertia H[s] is calculated on the basis of an estimated online generators capacity. The larger the area, the more stored energy in the rotating masses of the synchronous generating units there is inherently that the system can benefit from. Inertia contribution from demand is neglected, it has been considered that the self-regulating effect of loads is decreasing from the traditional value of 1–2 %, which provides a conservative approach without impact on the trend identification and scale of the challenge.



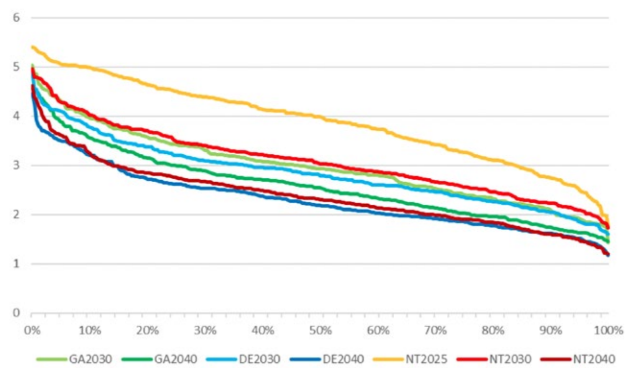
Synchronous Area Inertia (H[s]) – CE



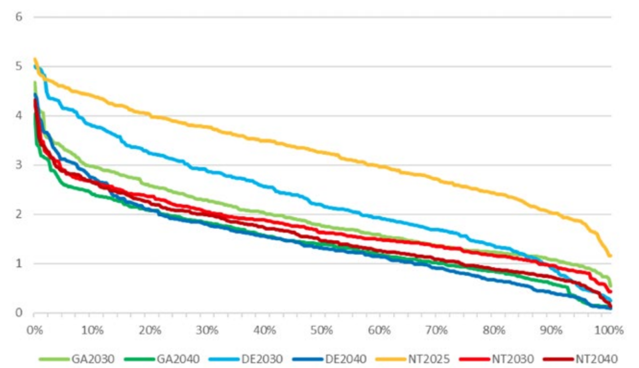
Synchronous Area Inertia (H[s]) – Nordic



Synchronous Area Inertia (H[s]) – Baltic



Synchronous Area Inertia (H[s]) – IE

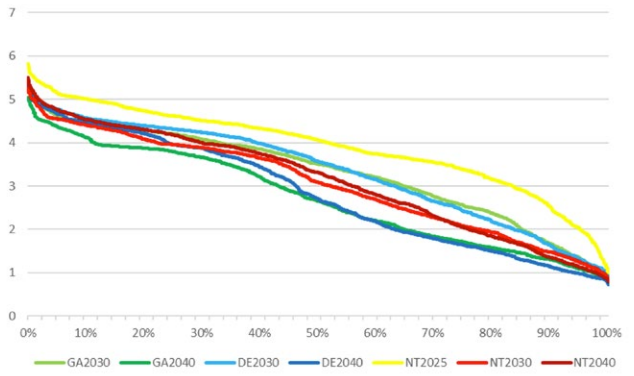


Synchronous Area Inertia (H[s]) – GB

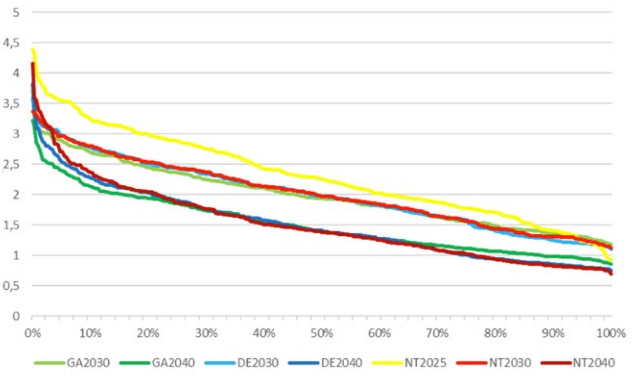
System inertia trends

As we move from the situations in 2025 to the 2030 and 2040 visions with a higher integration of RES and more distributed generation, inertia in all synchronous areas will decrease. The reduction is noticeable even in large area such as Continental Europe.

With very low inertia, the system becomes more vulnerable to experience high frequency excursions and even blackout as result of a relatively low mismatch between generation and demand. The impact of this inertia reduction is especially significant in small synchronous areas.



Synchronous Area Inertia (H[s]) – Main Italian Peninsula

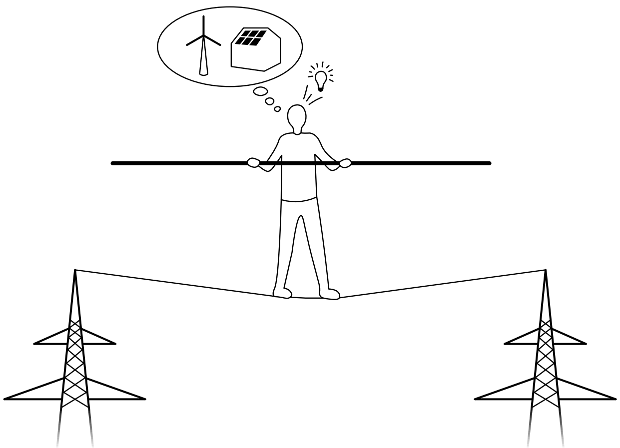


Synchronous Area Inertia (H[s]) – Iberian Peninsula

The above duration curves present the percentage of hours in a full year where the intrinsic inertia from generators, in the main Italian peninsula and the Iberian Peninsula, is above a given value.

Given the trend of more non-synchronous sources without intrinsic inertia, the same level of imbalance between generation and demand today will create a faster and greater change in system frequency in the future. This is because of the reduced levels of inertia to oppose this change. This trend towards higher frequency sensitivity to incidents for generation-demand imbalances is important to quantify. If frequency changes to quickly or far from nominal the system may become unrecoverable and blackouts will occur.

Whereas small synchronous areas would see large and rapid frequency excursions that could last for several tens of seconds after a normal generation loss, large synchronous areas would see smaller frequency excursions (unless a significant disturbance occurs such as a system split event).



The behaviour of RES units must be further developed so that they react immediately to deviations …

The enhanced capabilities will be as more effective to the system as they are more widespread and across all voltage levels …

A system split is more prone to occur across congested transit corridors and thus interrupting these transits. As transfer of power is increasing in magnitude, distance and volatility, the power imbalance following a system split event is likely to increase. This will need to be compensated by fast frequency response including fast control reserves or frequency related defence measures, e.g. the Limited-Frequency-Sensitive-Mode Over-frequency technical capability of generators or Low Frequency Demand Disconnection (LFDD).

In a system split event the synchronous area splits into separate islands. In this situation the resulting imbalances and the resulting equivalent system inertia in each island will depend on the specific conditions in the instant they occur. Under those conditions, it is reasonable to consider the existence of large initial rate-of-change of frequency (ROCOF) exceeding 2Hz/s (typical value for defence plans and RfG withstand capability for generators). Defence plans[8] are designed to help during severe disturbances but cannot stabilize all system split scenarios with extreme imbalances.

8 According to the SOGL: system defence plan means the technical and organisational measures to be undertaken to prevent the propagation or deterioration of a disturbance in the transmission system, in order to avoid a wide area state disturbance and blackout state.

Different solutions and mitigation measures contribute to securing the power system performance in case of disturbances related to frequency (such as synchronous condensers). These services are more difficult to be obtained from variable renewables, and significant effort is likely to be needed to develop the existing capacities and bring new promising technologies into the system such as Grid-forming Converters (GFC).

Grid-forming Converters are power electronics devices designed in control and sizing in order to support the operation of an AC power system under normal, disturbed, and emergency conditions without having to rely on services from synchronous generators. The technology is still under definition. Research is still ongoing as characteristics are still being shaped in concert with the changing needs of power systems around the world. In this context, ENTSO-E established the technical group HPoPEIPS (High Penetration of Power Electronic Interfaced Power Sources) with the purpose of analysing the grid forming capabilities according to the system needs, considering also the existence of current converter technologies[9], i.e. grid following converters.

The constructive dialogue between all involved parties, TSOs, DSOs, research institutes, manufacturers, system users and policy makers, should start now to define the relevant technical requirements for those capabilities, replacing missing capabilities inherent to synchronous generators, and a roadmap to make them available to the system in time.

Flexibility aspects

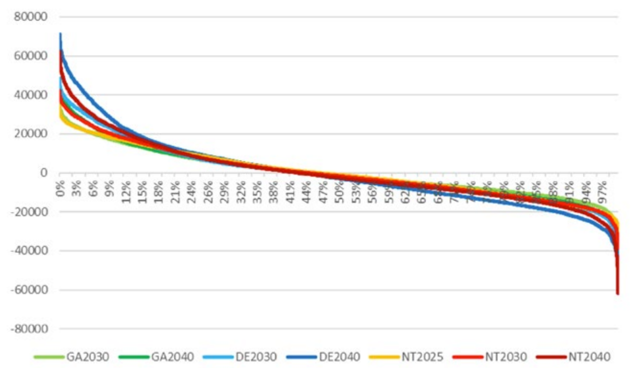
Unlike conventional generation with costly but controllable sources of primary energy, RES utilize primary energy sources that are free but have a variable nature. Hence, the high installed capacity of RES and their close-to-zero marginal costs cause conventional generation to be displaced from the market.

The variability in the power output from RES, which is driven by the variability of the primary energy resource, must be balanced, including forecast output deviations. The response (in MW/hour) that needs to be provided by controllable resources (generating units, demand and storage) to maintain the balance between generation and demand provide an additional measure into the challenges of operating a system with reduced amount of controllable generating units, high flexibility needs in normal operation, and a requirement to guarantee the necessary volume of frequency reserves in all timescales for the cases of unforeseen imbalances between active power generation and demand.

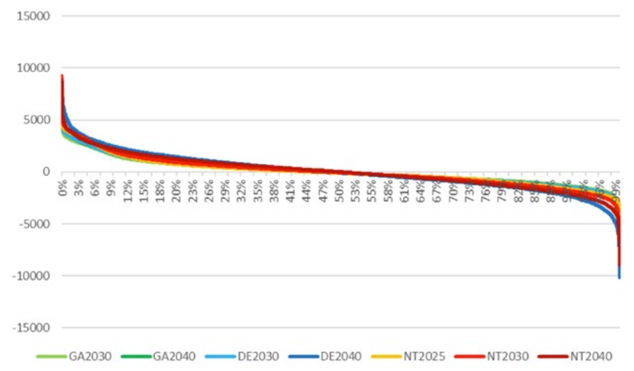
Residual load ramps exhibit the changes of residual load (all demand minus variable RES) from one hour to the following hour. These curves express the response (in MW/hour) that needs to be provided by controllable resources (generating units, demand and storage) in order to maintain balance between generation and demand. They also provide an additional measure into the challenges of operating a system with reduced amount of controllable generating units, high flexibility needs in normal operation, and a requirement to guarantee the necessary volume of frequency reserves in all timescales for the cases of unforeseen imbalances between active power generation and demand.

The following plots display the duration curves of residual load ramps as the changes of residual load from one hour to the following one in a synchronous area on a full year. RES includes all RES sources except hydro.

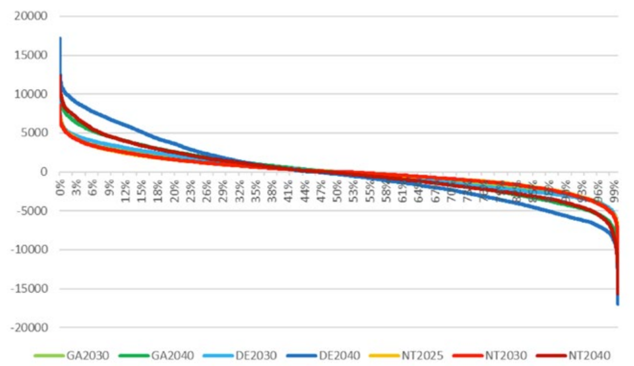
9 Other relevant projects, such as MIGRATE (https://www.h2020-migrate.eu/) and OSMOSE (https://www.osmose-h2020.eu/) accounted with the collaboration of TSOs.



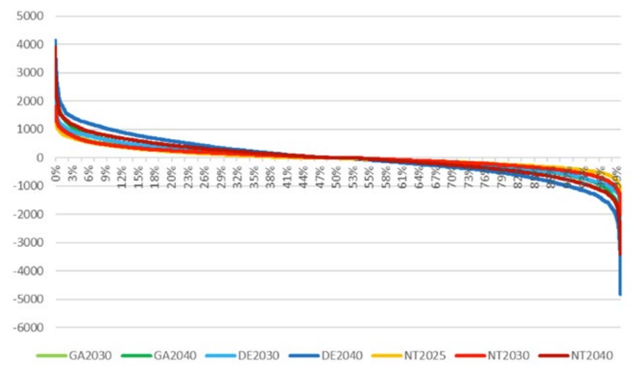
Hourly ramps of residual load (MW/h) – CE



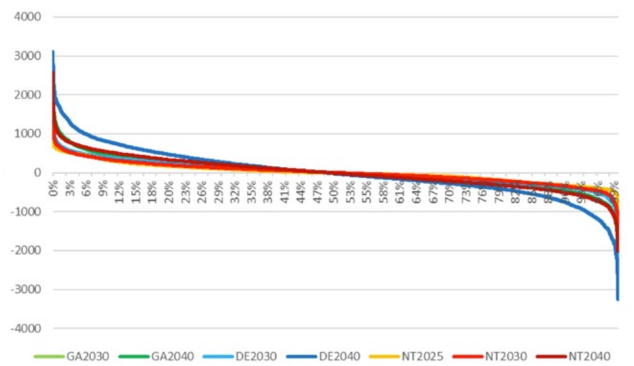
Hourly ramps of residual load (MW/h) – Nordic



Hourly ramps of residual load (MW/h) – GB



Hourly ramps of residual load (MW/h) – IE



Hourly ramps of residual load (MW/h) – Baltic

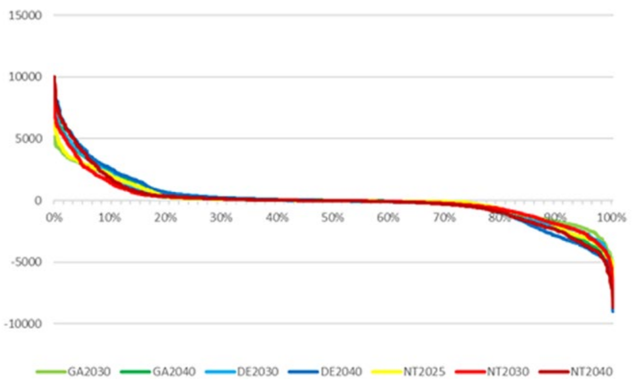
Residual load ramps

High response (in MW/hour) that needs to be provided by controllable generating units in order to maintain balance between generation and demand is verified in all synchronous areas.

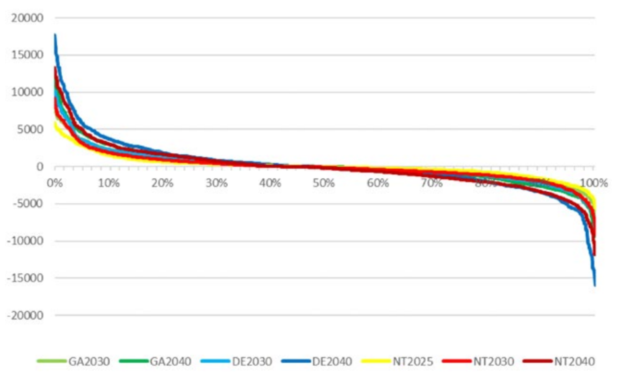
It is necessary to guarantee the necessary volume of frequency reserves in all timescales for the cases of unforeseen generation and demand imbalances

Flexibility sources will be necessary both from the generation and demand side.

Strong interconnection between countries will be essential to exchange the power flows from flexibility sources.



Hourly ramps of residual load (MW/h) – Italy



Hourly ramps of residual load (MW/h) – Iberian Peninsula

In a more detailed example, the above plots display the duration curves of residual load ramps as the changes of residual load from one hour to the following one in the main Italian peninsula and in the Iberian Peninsula.

In order to cope with this situation new flexibility sources will be necessary both from the generation, storage and demand side. This includes new roles for thermal plants, RES participation, demand side response, and storage. Also from the network side, strong interconnection between areas of production and consumption will be essential to enable the power flows from flexibility sources.

Investments to allow large power flows covering vast distances, flexibility rewards to providers (also at a local level) and innovations in power electronics (inverters) will be central aspects to the solution.

Transient and voltage stability related aspects

Short-circuit power

Short-circuit power has been commonly used as an indicator of the system strength and, consequently, the ability of a synchronous generating unit to remain connected to the network following a large disturbance and remain in synchronism with the system. A strongly meshed system with enough synchronous generation running at all times will have a high short-circuit level.

Synchronous generation provides greater short circuit current than equivalently rated converter connected RES. Therefore as it is replaced by RES, the short circuit level will reduce. Also the contribution of a generator to provide short circuit power reduces the further away it is, so as the power generated has to be transmitted by over a long distances to demand centres, the short-circuit power level will drop to very low levels.

This will result in faults causing deeper voltage dips, affecting the efficiency and security of the system.

Reactive power fluctuations

A constant and reliable source of reactive power is essential to maintain system voltage, a shortfall will reduce voltage and an excess will raise system voltage. Both high and low voltages can lead to equipment failure, and consequentially loss of demand and ultimately blackouts. Some reactive power devices on the system also monitor and try to respond to correct any excess or shortfall accordingly. Fluctuations can also lead to errors in these corrective actions which can also impact on security of supply.

The fluctuations in reactive power demand and reactive losses are increasing. This is driven by a number of factors including:

- the higher reactive power losses associated with larger power transits;
- the reduced reactive demand due to the changing nature of the demand, and;
- the increased reactive gain from lightly loaded circuits during low demand periods or during times of high output of embedded generation.

The large fluctuations in reactive power demand and reactive losses and the reduction in short-circuit power generally result in an increase in both instantaneous change in voltage (voltage step) and the final settled voltage after automated corrective actions have occurred (post-fault voltage).

The technological capabilities of transmission connected synchronous generation to provide or absorb reactive power is generally significantly higher compared to embedded RES with convertor power electronic interfaces. Therefore, reactive power reserves available on the transmission system are diminishing as mainly convertor connected RES replaces synchronous connected generation and some of this generation will connect to the distribution system. Due to this fact it is necessary to ensure that sufficient alternative measures are made available in order to ensure that voltage excursions can be managed within permissible limits. As seen above, a uniform distribution is the most effective way to control the system voltage. Given the high variability of power transits and generation mix combinations a good mix between network-based solutions and generator-based solutions will be necessary.

The exact location and technology of projects to address the assessed needs for increased capacity in 2040 is not known at this time. These will be highly influential on the future changes in system strength and reactive power provision compared to those at present. Consequently, the corresponding projects to compensate these changes to provide adequate dynamic behaviour can also not be determined at this time. However, ENTSO-E is committed to and will conduct further studies to assess the mitigating needs and projects for the scenarios 2040 as capacity related projects are developed.

How to adapt? Possible solutions for future system operations

The situation described above and in more details in the side-report *System dynamic and operational challenges* will lead to new needs, whose exact nature and scale will need to be assessed in detail by System Operators. These are expected to require significant Research and Development efforts as well as a redefinition of the roles and responsibilities of system participants, and possibly new cross border and internal transmission lines. The possible solutions could include:

- The connection codes technical requirements are essential to ensure that the necessary technical capabilities from generators, HVDC and demand related to dynamic stability are enabled.
- In the future new capabilities, not yet available, such as grid-forming converters[10] are currently promising to be capable of providing immediate inertial response. Grid forming converters will need research and development so they could prove to be a solution and can in the future be incorporated in the grid[11]. TSOs, DSOs, manufacturers, research institutes and policy makers must make an effort in establishing the scenarios where Grid-forming Converters (GFC) are needed and thus, GFC technical requirements must be clearly defined in the future.
- Immediate inertial response can only be presently met by synchronous generators. After immediate inertial response, fast frequency response by other sources than synchronous generation are needed: converter-connected generation, demand side response, storage (including batteries), and reserves shared between synchronous areas using HVDC.
- Dynamic system needs could lead to a limitation of cross border exchanges between large and small synchronous areas in some situations.
- New roles for existing generators, who would become service providers able to react to changing operating conditions in real time, temporarily or permanently for instance from decommissioned nuclear power plants (Germany).
- Real-time monitoring of system inertia to ensure minimum level of inertia is in the system at all times.
- Procurement of inertia and reactive power as an ancillary service and activation when necessary (e.g. during high RES production), using possibly aggregated sources coordinated with DSOs.
- Constraining RES and placing synchronous generation with intrinsic inertia in the unit commitment. This measure, which is easy to implement as a short-term solution could be less efficient in the long term.
- Investments on the network side: Additional voltage-supporting units are required in the transmission network. These units (synchronous condensers, SVCs, STATCOM, HVDC especially with grid forming capabilities) must be well distributed so that the various situations and faults can be handled, maintaining stability and avoiding curtailment of RES generation.
- Observability and controllability of distributed resources by the TSOs and DSOs as well as strong coordination between both operators.

10 Implementation Guiding Document – High Penetration of Power Electronic Interfaced Power Sources.

11 An example of related investigations is the MIGRATE project – Massive InteGRATion of power Electronic devices.

6 Next steps

New projects to address the needs

ENTSO-E expects that System needs study results will allow promoters to study new projects for the long term addressing the newly identified needs. That is why ENTSO-E is opening on the date of publication of this report a second submission window to the TYNDP 2020, opened only to projects commissioning after 2035 addressing system needs identified in the current System needs study or not captured by this study due to limitations of the methodology. These Future projects will be assessed in the TYNDP 2020 with a subset of CBA indicators. CBA results are expected to be released by early November, in addition to the 171 projects already included in the TYNDP 2020 portfolio.

A closer look at 2030

To support the 5th PCI process, ENTSO-E released in addition to this report brief reports providing an overview of needs in 2030 at PCI Corridor level (Power System Needs Briefs) and at country level (Country Factsheets).

Cost-benefit analysis of transmission and storage projects

The TYNDP 2020 will perform a cost-benefit analysis of 146 transmission and 25 storage projects[12] and evaluate how they contribute to meeting the system needs for 2030. The CBA considers a wide range of indicators and for the 2030 horizon will assess projects in two scenarios in addition to National Trends. The consistency between the findings of the System needs study for the 2030 horizon and the CBA results will be analysed and an overview will be included in the TYNDP 2020 report, expected to be released by November 2020.

Public consultation and ACER opinion

This System needs report and the six Regional investment plans published alongside it will be submitted to a public consultation alongside the rest of the TYNDP 2020 package. The public consultation is foreseen to begin in November 2020 and to last six weeks. Stakeholders comments will serve to improve the reports. Comments regarding the methodology itself will be taken into account to improve the future editions of the System needs study, as the available time does not allow to re-run the study.

In January 2021, the entire TYNDP 2020 package will be submitted to ACER for Opinion. ACER's comments will be implemented as far as possible in this edition of the System needs study, or alternatively considered for implementation in future System needs studies.

Perspectives for future System needs studies

Each new release of the System needs study allows the needs behind projects to be monitored in future years so that as and when needs change, because new scenarios are being investigated, projects may be confirmed or redefined. The System needs study is an evolving tool to manage increasing uncertainty in the context of the energy transition. Perspectives for future System needs studies are diverse and will be discussed with ACER and the European Commission.

12 Draft list of projects in the TYNDP 2020 portfolio

7 IoSN Methodology

The process to identify system needs can be divided into two main steps: (1) the preparatory step in which the inter-zonal impedances, capacities and loop flows are determined and bundled as constraints for the zonal model and (2) the implementation phase where necessary grid reinforcements are identified and quantified in their impact on the change in social-economic welfare, CO_2 emissions and RES-penetration. The outcome of the System Needs study is a list of target capacities that provide the most economically efficient means of reducing cross-border congestion and total system costs.

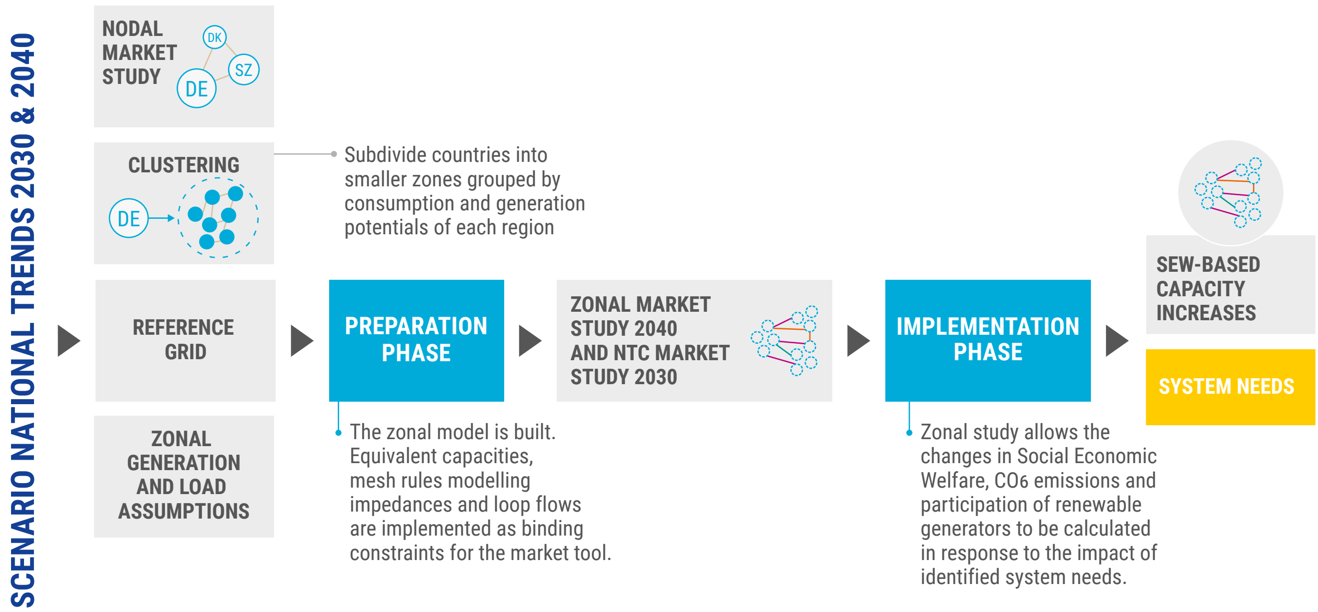


Figure 7.1 – Overview of the IoSN inputs, process and outputs

The scenarios

The TYNDP 2020 Scenario edition published in June 2020 represents the first step to quantify the long-term challenges of the energy transition on the European electricity and gas infrastructure.

The joint work of ENTSO-E and ENTSOG, stakeholders and over 80 TSOs covering more than 35 countries provided a basis to allow assessment for the European Commission's Projects of Common Interest (PCI) list for energy, as ENTSO-E and ENTSOG progress to develop their respective TYNDPs.

We strongly recommend the reader familiarises themselves with the content included in the **Scenarios Report** and **Data visualisation platform**, as these provide full transparency on the development and outcomes of the scenarios mentioned in this report.

ENTSOs 2020 scenarios

The joint scenario building process presents three storylines for TYNDP 2020

National Trends (NT), the central policy scenario, based on the Member States National Energy and Climate Plans (NECPs) as well as on EU climate targets. NT is further compliant with the EU's 2030 Climate and Energy Framework (32 % renewables, 32.5 % energy efficiency) and EC 2050 Long-Term Strategy with an agreed climate target of 80–95 % CO_2-reduction compared to 1990 levels.

Global Ambition (GA), a full energy scenario in line with the 1.5°C target of the Paris Agreement, envisions a future characterised by economic development in centralised generation. Hence, significant cost reductions in emerging technologies such as offshore wind and Power-to-X are led by economies of scale.

Distributed Energy (DE), a full energy scenario as well compliant with the 1.5°C target of the Paris Agreement, presents a decentralised approach to the energy transition. On this ground, prosumers actively participate in a society driven by small scale decentralised solutions and circular approaches. Both Distributed Energy and Global Ambition reach carbon neutrality by 2050.

The scenarios are referred to simply by their names (National Trends, Global Ambition and Distributed Energy) to reduce redundancy.

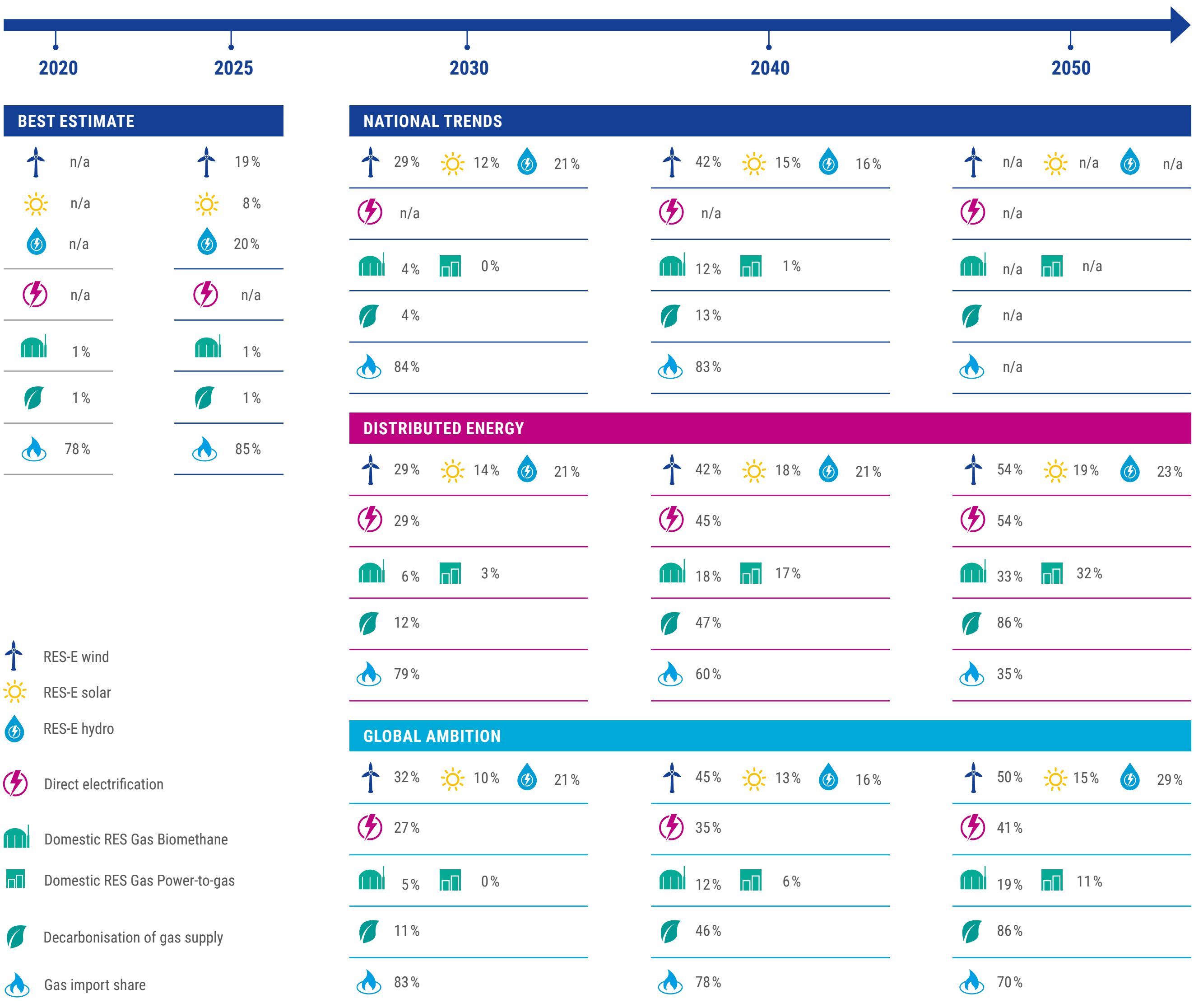


Figure 7.2 – Key parameters of the TYNDP2020 scenarios storylines

Bottom-Up: This approach of the scenario building process collects supply and demand data from gas and electricity TSOs.

Top-Down: The "Top-Down Carbon Budget" scenario building process is an approach that uses the "bottom-up" model information gathered from the Gas and Electricity TSOs. The methodologies are developed in line with a Carbon Budget approach.

Full energy scenario: a full energy scenario employs a holistic view of the European energy system, thus capturing all fuel and sectors as well as a full picture of primary energy demand

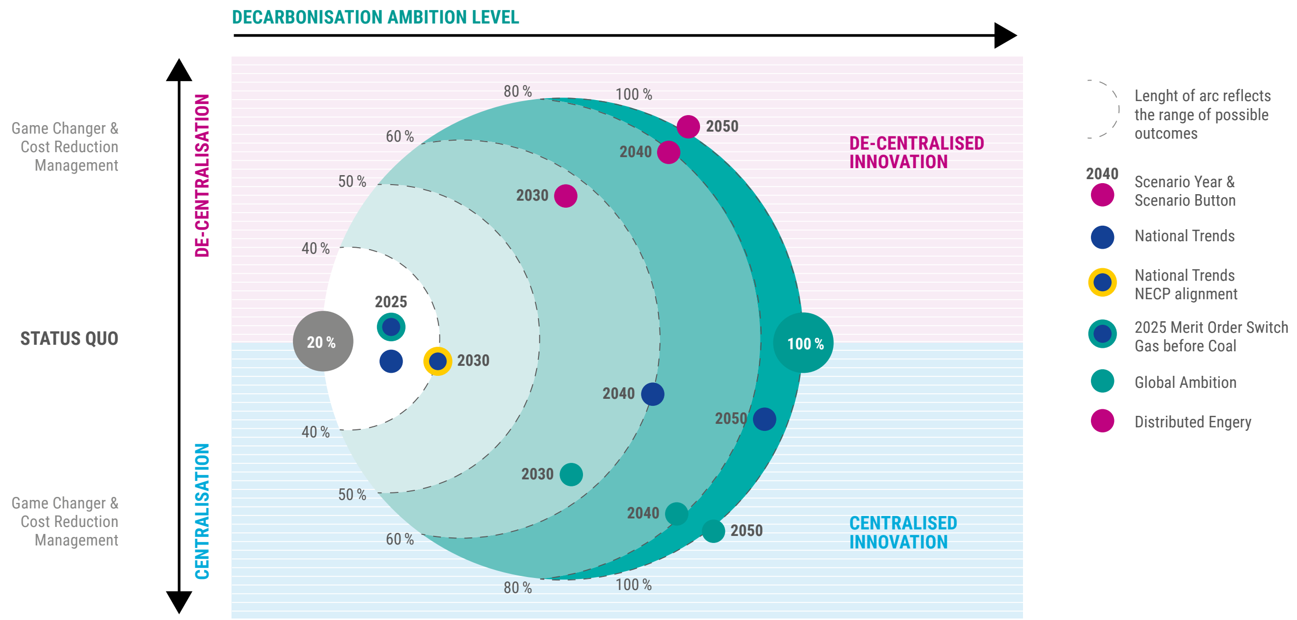


Figure 7.3 - Key drivers of scenario storylines

Central role of National Trends in the System Needs study

National Trends is the central scenario of the TYNDP 2020 and the only scenario employed in the System needs study. Because it was designed to reflect EU Member States' National Energy and Climate Plans (NECP), its use ensures the relevance of identified needs with respect to EU energy and climate targets.

In the next phase of the TYNDP, a cost-benefit analysis (CBA) of electricity transmission and storage projects will be performed for National Trends (2025 and 2030 time horizons). Additionally, to illustrate the robustness of the proposed infrastructure projects, they will also be assessed with a subset of CBA parameters for Distributed Energy and Global Ambition scenarios (2030 time horizon). Projects will also be assessed in a 'Current Trends' sensitivity, as requested by ACER.

National Trends alignment with NECPs

The bottom-up scenario National Trends relies on best-available information for the timeframe 2020 to 2040, directly collected from the gas and electricity TSOs. The National Trends related data collection provided an important opportunity to collect in-depth information stemming from the National Energy and Climate Plans, National Development Plans and other nationally recognized studies. Since most of the NECPs are based on an impact assessment until 2030, the TSOs' knowledge was key to build a consistent scenario until 2040.

National Trends follows the trends developing the climate policies on a national level. The governance of the energy union and climate action rules, which entered into force on December 2018, requires EU member states to develop NECP that cover the five dimensions of the energy union (Regulation on the governance of the energy union and climate action (EU/2018/1999)) for the period 2021 to 2030 (and every subsequent ten year period). Member States had to submit draft NECPs by 31 December 2018. Most of the draft NECPs provide an impact assessment regarding energy consumption and supply and ensure that the Union's 2030 targets for greenhouse gas emission reductions, renewable energy, energy efficiency and electricity interconnection are met.

After NECPs submission by Member States on December 2018, the European Commission published its review on June 2019, including specific recommendations. Member States were then required to update their NECP and submit a final version to the European Commission possibly by the end of 2020.

Scenarios outlook for power to gas

Power to gas: Technology that uses electricity to produce hydrogen (Power to Hydrogen – $P2H_2$) by splitting water into oxygen and hydrogen (electrolysis). The hydrogen produced can then be combined with CO_2 to obtain synthetic methane (Power to Methane – $P2CH_4$).

With increasing climate ambitions and progressing energy transition both the electricity and gas sector face challenges to achieve the decarbonisation target, and one of them is the interaction of these two sectors. Renewable electricity generation is usually asynchronous and at present, the electricity grid is pushed to its limits in the integration of further variable generation. On the other hand, the gas sector needs to be decarbonised in order to be able to implement an option in a strongly or completely decarbonised energy system. Power to gas offers a solution to both problems, relieving stress in the electrical grid by storing excess electricity from renewables in carbon neutral gaseous fuels.

ENTSO-E and ENTSOG have assessed the integration of P2G facilities in their scenarios by developing methodologies for their quantification, distribution and optimisation. For instance, in National Trends the economic viability of Power to Gas facilities is quantified by calculating the minimum full load hours for the facility to be economic viable in a country. The actual P2G production can vary depending on other factors, such as the distance of the RES facilities to the grid and the local excess electricity duration curve. A detailed description of this and the P2G methodologies used for Distributed Energy and Global Ambition (National Trends considers the information provided by TSOs and NECPs) can be found in the **Scenario Building Guidelines**.

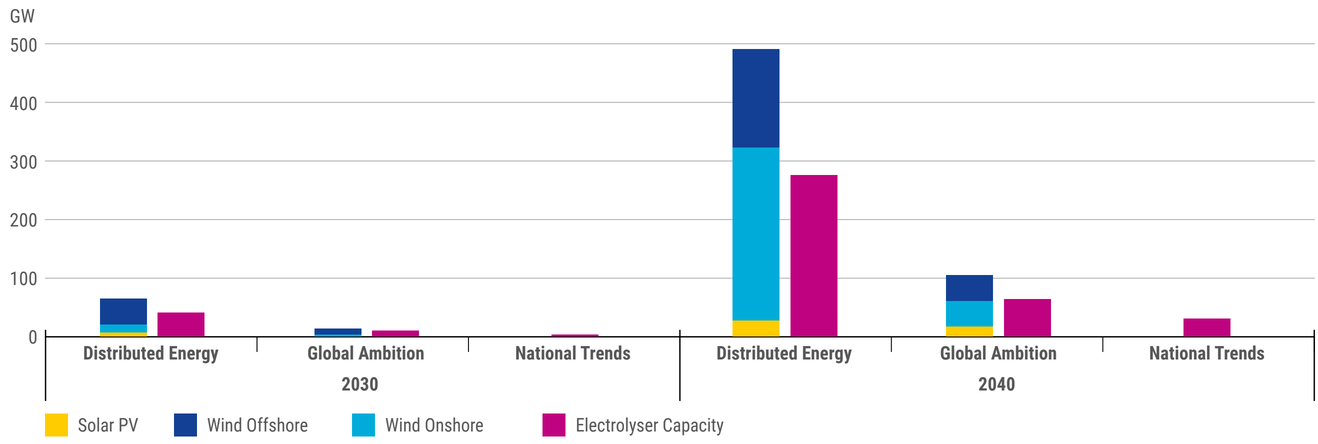


Figure 7.6 – Capacity for hydrogen and derived fuels production

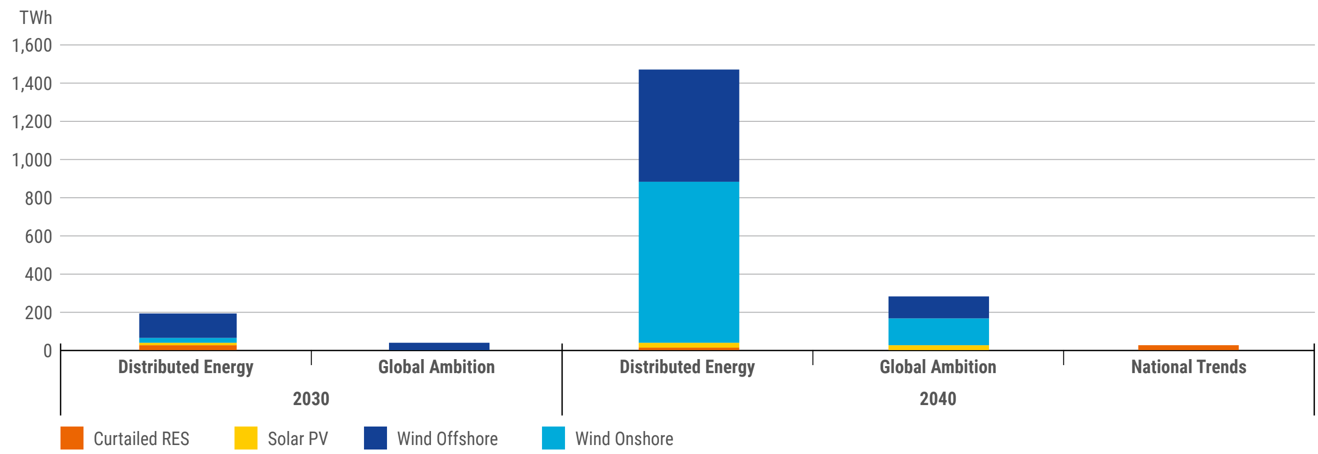


Figure 7.7 – Generation mix for hydrogen and derived fuels production

The reference grid: starting point of the identification of system needs

Every study of the transmission grid aimed at identifying system needs requires a single reference point against which all scenarios and needs combinations can be compared to. This single reference point, called 'reference grid', is usually composed of the existing grid and of the projects that are likely to be implemented by the date of the scenario that is considered in the study.

In the TYNDP 2020, the same reference grid is being used for the identification of system needs and for the cost-benefit analysis of projects (included in the TYNDP 2020 report, to be released later this year). Figure 7.8 illustrates how the reference grid serves as starting point for the System Needs study.

Role of the Reference Grid in the System Needs Studies: starting Point

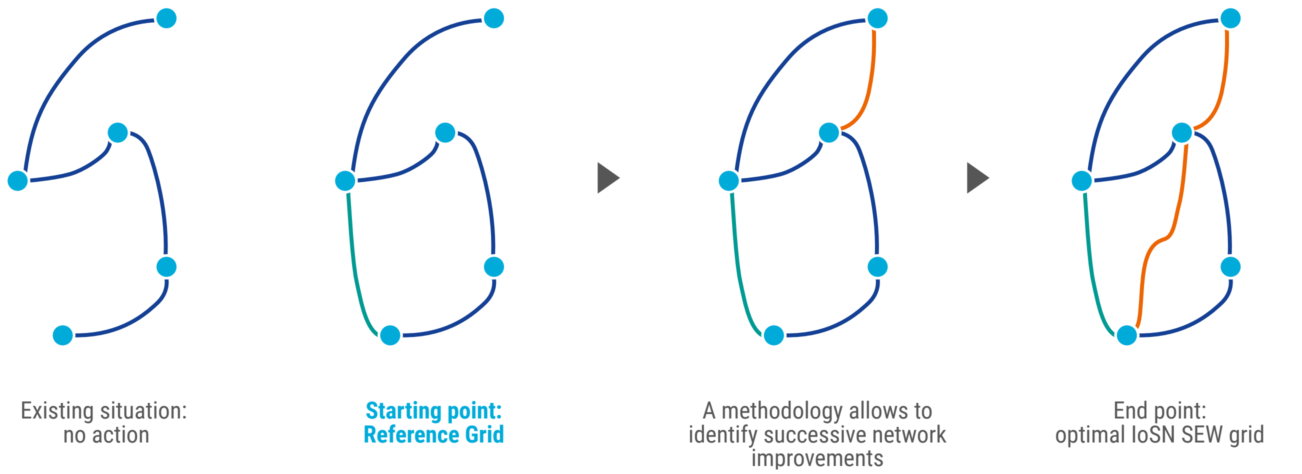


Figure 7.8 – Role of the Reference Grid in the System needs study

Elements taken into consideration when building the starting point

Lessons learnt from the TYNDP 2018

In 2018 as in previous TYNDPs, the reference grid was built based on fixed criteria including the commissioning year and project status. This approach presented two major drawbacks: Fixed criteria have the inconvenience of not being consistently applicable across Europe, because they rely on indicators which are not consistently described in all European countries. For instance, the stages of the permitting procedure differ among countries. Additionally, some criteria, such as the commissioning year, rely on information supplied by project promoters and is not verifiable by regulatory authorities or by ENTSO-E.

To maximise the reliability of the results, a realistic and technically sound starting point is required. More specifically, the reference grid for the system needs study should strike a balance between an unnecessarily underestimated grid and an overly-developed one:

- On the one hand, the reference grid should include at least the most mature projects. These include the transmission projects that are currently under construction and those in the permitting process for which it is fairly certain that they will be completed by the year considered as the reference. When commissioned, these projects will address system needs already identified in previous TYNDPs. By including these projects in the reference grid, the study will more accurately show the needs for less certain additional reinforcements to the system.

- On the other hand, the reference grid must be compact enough to identify areas where the current projects are not sufficient to respond to the system needs, and to check whether planned projects exceed the system needs. Results will then allow to confirm existing projects or redefine projects' scope and timeline.

Compliance with the CBA Guideline

According to the draft CBA Guideline 3.0, only those projects whose timely commissioning is reasonably certain can be included in the reference grid, and if the study involves countries with different procedures regarding the permitting process, which is the case of the System Needs study, the CBA Guideline recommends to apply expert's judgement supported by studies with a conservative forecast of the future grid, such as ENTSO-E's Mid-Term Adequacy forecast (MAF)[13].

13 For more details, read the draft **CBA Guideline** (3rd CBA Guideline for cost benefit analysis of grid development projects, version submitted to ACER for opinion, February 2020)

Step 1: MAF 2025 as a basis

Considering the elements detailed above, ENTSO-E decided to use the MAF 2019 grid as the base for the TYNDP 2020's reference grid. The MAF grid contains all projects under construction or for which there is a high confidence in their availability, high enough to be used as a basis for security of supply analysis. It is built for the year 2025 and is based on expert knowledge.

Because it is used for adequacy assessment, the MAF 2019 reference grid (hereinafter MAF2025) is conservative by nature. Adequacy studies require realistic assumptions on the network and market capacity available. Overestimated available interconnection capacities would lead to underestimating adequacy issues while underestimating network capacities would most likely lead to overestimating adequacy issues in the mid-term.

Step 2 – Expert view

The MAF2025 grid consists of net transfer capacities (NTCs) per border and direction that are not attributed to specific transmission projects. To build the TYNDP 2020 reference grid, TSO experts had to attribute these NTCs to specific projects to prepare the inputs for the methodology implemented for this TYNDP, more on this below. This was done by adding to the existing network a list of projects (internal or interconnectors), either already under construction or foreseen to be available by 2025, that, aggregated, matched the expected transfer capacities.

Step 3 – Input of ACER and NRAs

ENTSO-E shared an initial version of the reference grid with the European Commission, ACER and national regulatory authorities in June 2019. ACER and NRAs provided recommendations for projects to be included or excluded, according to fixed criteria chosen by ACER for inclusion of projects in the reference grid. This exchange allowed ENTSO-E to implement corrections and improve the robustness of the reference grid. However, ENTSO-E decided to keep the above-mentioned expert knowledge approach. Therefore, not all ACER recommendations have been implemented.

The list of projects considered in the reference grid is included in Appendix 2.

Zonal methodology for the identification of system needs in 2040

The main improvements developed in this release are considering market and network in one model together, and a model expansion algorithm. The objective with these improvements was to have more granularity than in previous System Needs exercises, consider physical flows (by considering Kirchhoff's Laws) but at the same time have reasonable computation times.

Therefore, for the purpose of the Identification of System Needs, a zonal model has been used. This zonal model represents a compromise between:

- Market simulations, which compute the optimal generation dispatch but for which the grid is only taken into account through the exchange capacities applied between bidding zones.
- Network simulations, which compute the flow on each line but for which optimal dispatch cannot be computed in reasonable time.

This methodology was already tested in the TYNDP 2018 process as an alternative approach of identification of system needs. The identification of system needs in 2018 was based purely on NTC with one zone per country. The zonal methodology was tested separately, based on the model developed by e-Highway2050.

The 2020 System needs study is based on about 100 nodes, a reduced grid model is produced to link these nodes with each other. Some constraints are applied on the links between nodes in order to simulate Kirchhoff's Laws. As a result, the optimal dispatch can be assessed at the European level, taking into account some physical limits on the network. This is a great advantage of this methodology that merged both market and network simulations in one single step avoiding loops between market and network models.

Division of Europe into zones

Starting from thousands of nodes over the pan-European network of the reference grid, the grid is reduced to a reasonable and workable number of zones (around 100). In order to better model the flow, this grid reduction has to take into account the bottlenecks that occur on the actual network.

For this study, the division has taken inspiration from the e-Highway 2050 study (2013). The criteria to select the zones were the administrative regions mixed with some adjustments in order to better fit network physical bottlenecks.

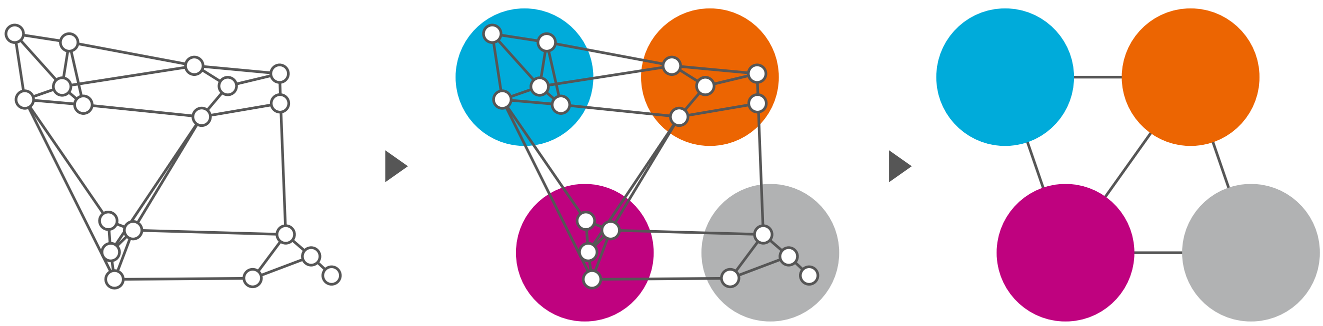


Figure 7.9 - Grid reduction: from a nodal to a zonal model (each circle represents a zone)

Generation and load assumption at zonal level

For each of the zones defined, the local electric system hypothesis, corresponding to the scenario under study, were collected:

- The installed capacity for each generation type;
- The load level taking into account the load types specific to each zone (industry, tertiary, residential area …).

The climate model is also differentiated into zones in order to take into account climate sensitive specificities of the zones (e.g. RES load factor, hydro inflows and thermal sensitive load). Thus, for each zone, the time series[14] for load, non-dispatchable generation, hydro inflows and thermal generation availabilities are defined. The sum, at country level, of these zonal hypotheses must result into the corresponding national hypothesis.

Grid reduction: from a detailed to a simplified AC network

Based on a detailed grid topology, a simplified network is built between the zones. This network must abide by Kirchhoff's voltage and current laws. To do so, each of the links has to be defined through dummy technical characteristics of the lines such as impedance and maximal capacities. These dummy technical characteristics are computed using the actual impedance and maximal capacities of each network component: they are obtained through an optimization process that minimizes the difference between the behaviour of this reduced grid and the one of the detailed network. With the dummy characteristics of the simplified network, Kirchhoff's circuit laws can be applied through binding constraints over the flow of each link. These constraints approximately mimic the flows seen on a detailed grid model[15].

Because the grid within a zone is not modelled, no congestion can occur inside a zone. But, in order to take into consideration that each zone is in reality made of several actual nodes, some loop flows are modelled on the reduced network.

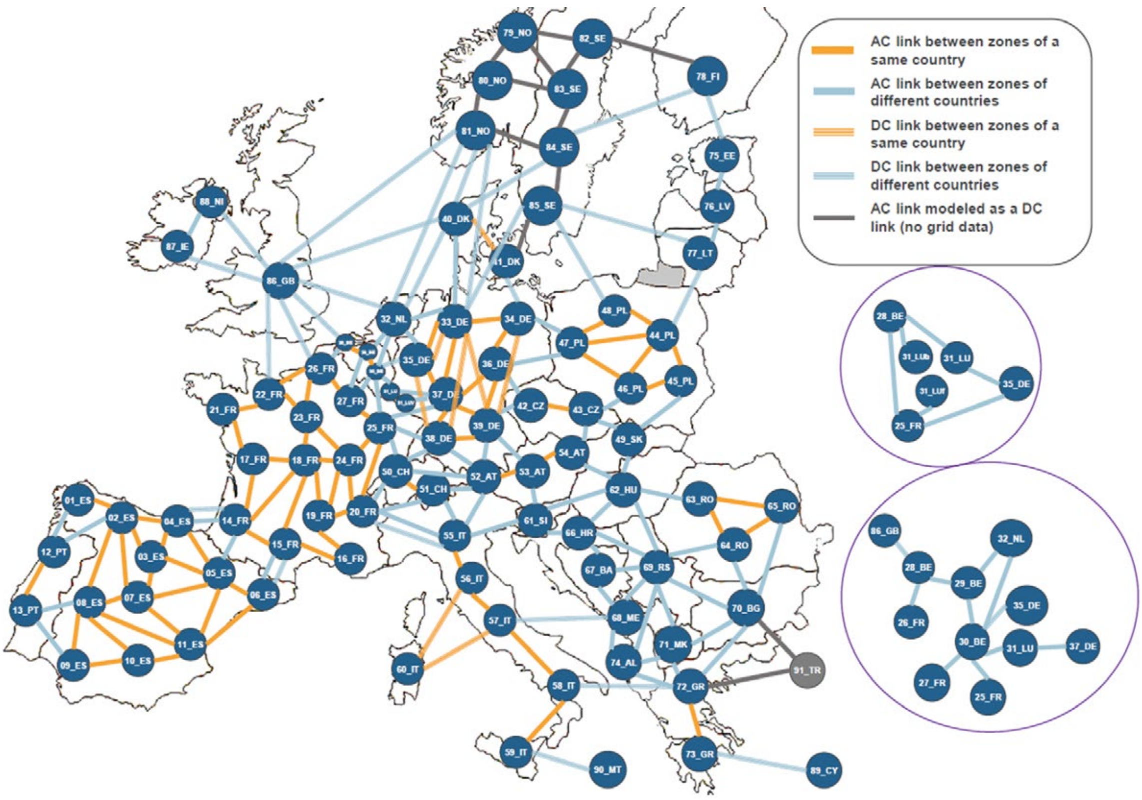


Figure 7.10 – European zonal model used for the identification of system needs (including the reference grid)*

* Countries outside of the ENTSO-E area, Turkey excepted, are not modelled. Exchanges are taken into account through a time series profile.

14 For different climate years

15 M. Doquet, "Zonal Reduction of Large Power Systems: Assessment of an Optimal Grid Model Accounting for Loop Flows," in IEEE Transactions on Power Systems, vol. 30, no. 1, pp. 503-512, Jan. 2015.

Expansion model and computation of needs

The System needs study assesses the potential optimal interconnection level between countries. Starting from the reference grid, an expansion model optimizes the total system costs based on optimal interconnection capacity increases. From a panel of possible network increases the model chooses the best combination that minimizes the total system costs, composed of total network investment and generation costs. The cost assumptions of the interconnection capacity increases are derived from the cost assumptions of the TYNDP 2020 projects and additional conceptual projects, provided by member TSOs, that are available at the assessed borders.

The optimisation plan is run on an expansion module that implements an iterative approach to reduce total system costs. This process is summarized in the following algorithm:

1. The expansion model selects a set of potential capacity increases from the available list[16].

2. The capacity increases are implemented on the zonal model. The investment costs are given by the costs assumptions provided by the available project portfolio.

3. A market simulation is run on an hourly dispatch on the zonal grid.

   a) The dispatch model outputs the optimal dispatch per hour in the target year and allows the total generation costs of the dispatch pool to be calculated.

   b) The total system cost is then computed by adding the investment costs of identified investment candidates to the previously calculated total generation cost. In other words, the total system costs can be calculated as following:
   Total System Costs
   = Total Generation Costs (existing dispatch units)
   + Total nework investment Costs (investment Candidates)

4. The expansion model assesses a lower bound to the total system costs.

5. If the difference between the resulting total system cost and the lower bound is greater than an acceptable range, the process returns to Step 1.

The final list of investments is the one that will give the total system cost closest to the lower bond.

The optimizer takes in the input all possible increases, but not all of them are included in the solution. If several projects are possible solutions to the same need, the optimizer will select the best one to fulfil the final objective of minimizing the total system costs.

With the resulting 2040 optimized grid, the benefits provided to the electric system by these investments can then be computed:

- The decrease of generation costs (socio-economic welfare) due to the additional possible exchange between countries.
- The CO_2 emission reduction due to the change in the generation plan.
- The reduction in curtailed energy due to the additional possible exchange.

16 At the first iteration, the set is chosen randomly, while at the following ones, it is chosen using the result of the previous iteration.

Standard Net Transfer Capacity model for 2030

For the horizon 2030, the System needs study did not use a zonal model but a standard net transfer capacity model (NTC), with a model that only considers one zone per country and the cross-border capacity is the NTC. The use of an NTC model for the 2030 horizon ensures consistency with the next phase of the TYNDP, i.e. the cost-benefit analysis of projects which also relies on an NTC model. Related to this alignment with the CBA, the NTC model included Tunisia, which is not included in the 2040 horizon.

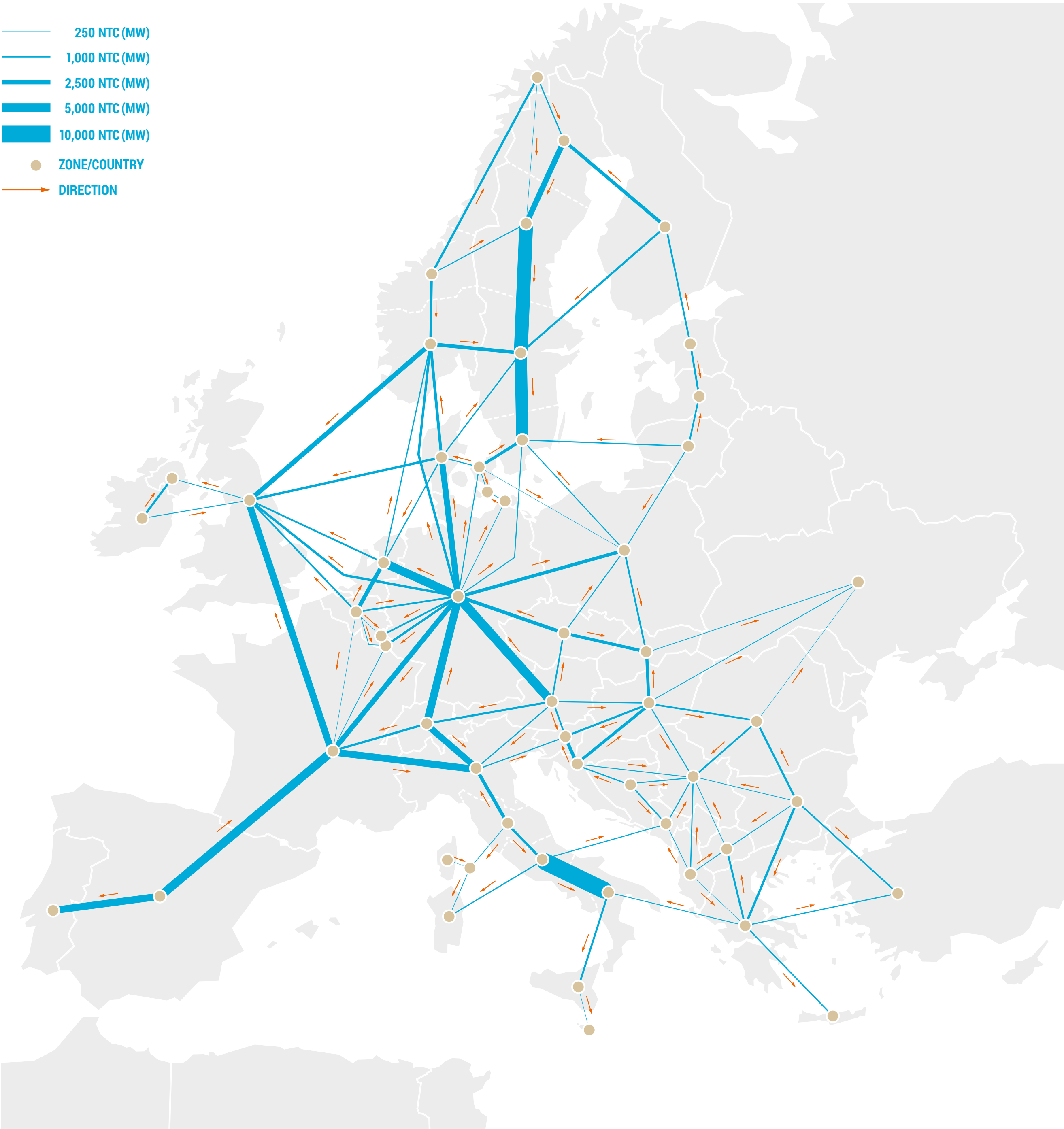
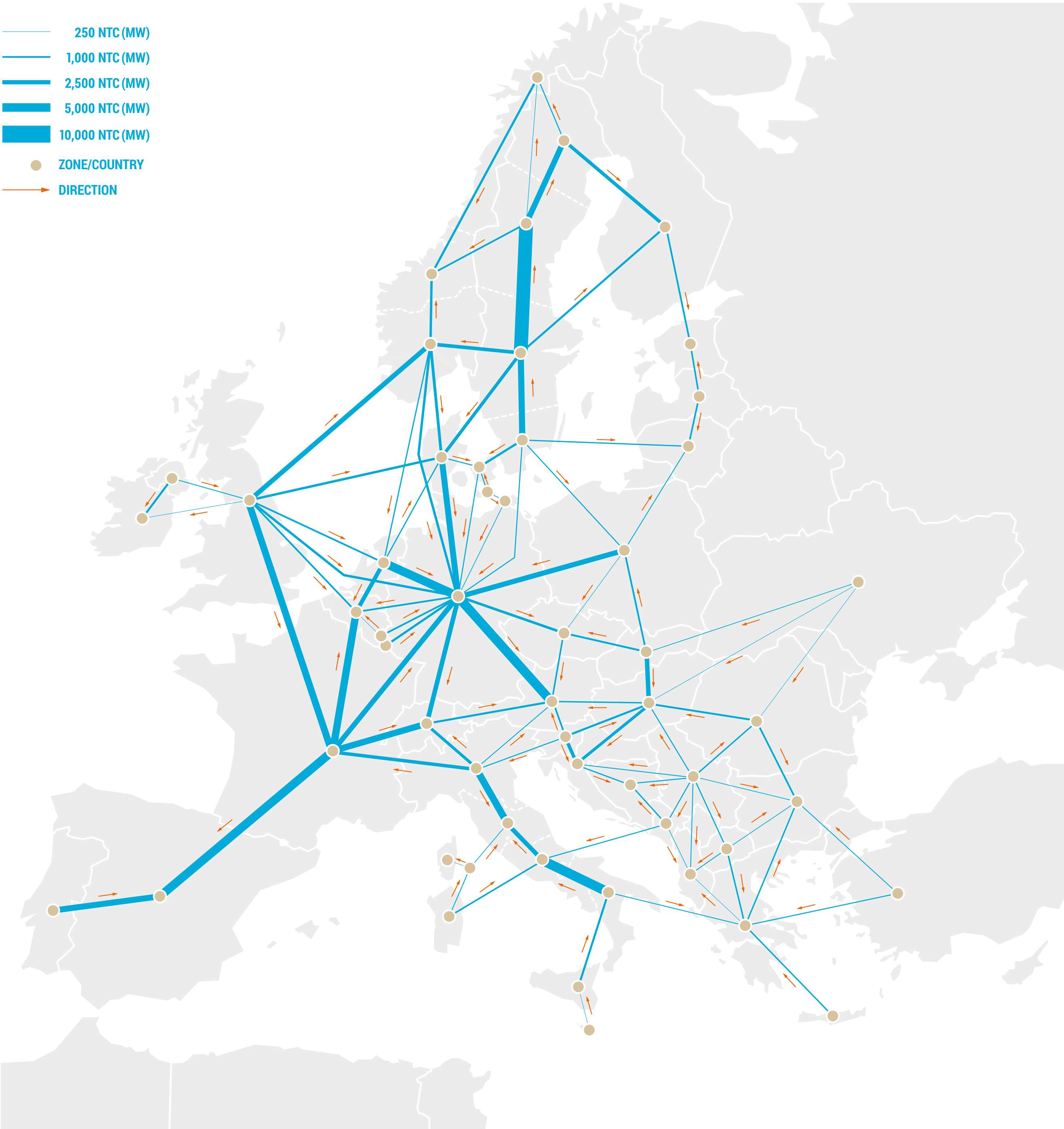


Figure 7.11 – NTC in 2025 in direct (left) and opposite (right) direction

These are the only two differences in methodology between the two time horizons. The methodology for the expansion model and computation of needs described in section 7.3.4 applies identically to the 2030 horizon.



Scope and limits of the identification of system needs

Like all modelling endeavours, the System needs study has a number of limitations related to the data, tools and assumptions used. It is important to note that the identification of system needs is a partial exercise and that different assumptions may lead to different conclusions. However, the numerous quality checks performed and the consistency checks done with the preliminary results of the cost-benefit analysis of TYNDP 2020 projects tend to confirm the robustness of the results.

A partial exercise focused on the optimisation of overall system costs

The System needs methodology is not designed to identify potential increases that might be beneficial on other grounds than overall system costs, such as improving security of supply or reduction of CO_2 emissions. However, benefits of capacity increases in terms of decreased CO_2 emissions are taken into account via generation costs and ETS CO_2 price.

Another limitation is that the current identification of system needs methodology does not identify offshore hybrid projects, i.e. the combination of interconnections and offshore generation. This is due to the fact that identifying optimal generation connection is not among the tasks of the TYNDP. Thus, generation units are generally part of the scenarios and the cost and routing of their connection to the network are not part of the System needs study optimisation task.

Among the costs considered, the identification of system needs methodology does not consider network losses. Losses of specific projects will be assessed in the costs-benefit analysis phase of the TYNDP.

Scenarios and climate year

The System needs study investigates one potential future, described in the scenarios National Trends 2030 and National Trends 2040. National Trends is aligned with the National Energy and Climate Plans of the respective Member States, which translate the European targets to country-specific objectives for 2030. Country-specific data was collected from TSOs for 2030 and 2040. Different assumptions, such as those made in other TYNDP 2020 scenarios Distributed Energy and Global Ambition, would likely bring different results.

System needs computations used data from ENTSO-E's pan-European Climate Database Climate for the year 2007. By comparison, the CBA of TYNDP projects is performed for three climate years, a wet year (2007), a dry year and an 'average' year. 2007 was chosen for the System needs study because it is more representative in terms of hours per year and weighs for 50 % in the CBA results. Because 2007 is a wet year, the values for expected generation capacities are not necessarily reflective of reality and may be subject to an over-estimation of hydro penetration. As hydro capacity plays an important role in the stability of the European system, acting as its international battery and providing significant balancing and inertial services, an over-estimation of this generation asset may distort the results slightly. The impact is likely the strongest on the results for Nordic countries with high share of hydro generation, for example when considering the net balance.

Costs data

As described in section 7.3.4, the optimisation model identifies the best combination of network increases that minimizes total system costs, composed of total network investment and generation costs. Regarding network investments, the cost assumptions of the capacity increases were collected from project promoters. Because their commissioning could be distant from now and because they are not yet precisely defined (some reinforcements correspond to completely new ideas), their costs are still uncertain. Because variations in costs may impact the outcome of the optimisation, an overview of network increases belonging to combinations of increases for which the total system cost is just slightly higher than that of the most cost-efficient combination has been investigated in Chapter 1.

In addition, costs are not fully reflective of costs associated with internal reinforcement and congestion management that would be required to make the increases in cross-border capacity possible. In many cases, in particular in Eastern Europe, increasing cross-border capacity would require significant reinforcement of internal networks because electricity tends to transit, crossing countries on its way from places with high RES generation to places with high load, or from places with lower prices to places with higher prices.

Modelling tool

Because of resources constraints, the decision was taken to run the study on only one tool (Antares). The consistency checks performed with the preliminary CBA results have shown that results are coherent.

Appendices

Appendix 1 – Glossary

Term	Acronym	Definition
Agency for the Cooperation of Energy Regulators	ACER	EU Agency established in 2011 by the Third Energy Package legislation as an independent body to foster the integration and completion of the European Internal Energy Market both for electricity and natural gas.
Baltic Energy Market Interconnection Plan in electricity	BEMIP Electricity	One of the four priority corridors for electricity identified by the TEN-E Regulation. Interconnections between Member States in the Baltic region and the strengthening of internal grid infrastructure, to end the energy isolation of the Baltic States and to foster market integration; this includes working towards the integration of renewable energy in the region.
Bottom-Up		This approach of the scenario building process collects supply and demand data from Gas and Electricity TSOs.
Carbon budget		This is the amount of carbon dioxide the world can emit while still having a likely chance of limiting average global temperature rise to 1.5 °C above pre-industrial levels, an internationally agreed-upon target.
Carbon Capture and Storage	CCS	Process of sequestrating CO_2 and storing it in such a way that it will not enter the atmosphere.
Carbon Capture and Usage	CCU	The captured CO_2, instead of being stored in geological formations, is used to create other products, such as plastic.
Combined Heat and Power	CHP	Combined heat and power generation.
Congestion revenue / rent		The revenue derived by interconnector owners from the sale of the interconnector capacity through auctions. In general, the value of the congestion rent is equal to the price differential between the two connected markets, multiplied by the capacity of the interconnector.
		The revenue derived by interconnector owners from the sale of the interconnector capacity through auctions. In general, the value of the congestion rent is equal to the price differential between the two connected markets, multiplied by the capacity of the interconnector.
Congestion		Means a situation in which an interconnection linking national transmission networks cannot accommodate all physical flows resulting from international trade requested by market participants, because of a lack of capacity of the interconnectors and/or the national transmission systems concerned.
	COP21	21st Conference of the Parties to the United Nations Framework Convention on Climate Change, organised in 2015, where participating states reached the Paris Agreement.
Cost-benefit analysis	CBA	Analysis carried out to define to what extent a project is worthwhile from a social perspective.
Curtailed electricity		Curtailment is a reduction in the output of a generator from otherwise available resources (e. g. wind or sunlight), typically on an unintentional basis. Curtailments can result when operators or utilities control wind and solar generators to reduce output to minimize congestion of transmission or otherwise manage the system or achieve the optimum mix of resources.
Demand side response	DSR	Consumers have an active role in softening peaks in energy demand by changing their energy consumption according to the energy price and availability.
e-Highway2050	EH2050	Study funded by the European Commission aimed at building a modular development plan for the European transmission network from 2020 to 2050, led by a consortium including ENTSO-E and 15 TSOs from 2012 to 2015 (**to e-Highway2050 website**).
Electricity corridors		Four priority corridors for electricity identify by the TEN-E Regulation: North Seas offshore grid (NSOG); North-south electricity interconnections in western Europe (NSI West Electricity); North-south electricity interconnections in central eastern and south eastern Europe (NSI East Electricity); Baltic Energy Market Interconnection Plan in electricity (BEMIP Electricity).
Energy not served	ENS	Expected amount of energy not being served to consumers by the system during the period considered due to system capacity shortages or unexpected severe power outages.
Grid transfer capacity	GTC	Represents the aggregated capacity of the physical infrastructure connecting nodes in reality; it is not only set by the transmission capacities of cross-border lines but also by the ratings of so-called “critical” domestic components. The GTC value is thus generally not equal to the sum of the capacities of the physical lines that are represented by this branch; it is represented by a typical value across the year.
Internal Energy Market	IEM	To harmonise and liberalise the EU’s internal energy market, measures have been adopted since 1996 to address market access, transparency and regulation, consumer protection, supporting interconnection, and adequate levels of supply. These measures aim to build a more competitive, customer-centred, flexible and non-discriminatory EU electricity market with market-based supply prices.

Term	Acronym	Definition
Investment (in the TYNDP)		Individual equipment or facility, such as a transmission line, a cable or a substation.
Mid-term adequacy forecast	MAF	ENTSO-E's yearly pan-European monitoring assessment of power system resource adequacy spanning a timeframe from one to ten years ahead.
Net transfer capacity	NTC	The maximum total exchange programme between two adjacent control areas compatible with security standards applicable in all control areas of the synchronous area and taking into account the technical uncertainties on future network conditions.
N-1 criterion		The rule according to which elements remaining in operation within a TSO's responsibility area after a contingency from the contingency list must be capable of accommodating the new operational situation without violating operational security limits.
National Energy and Climate Plan	NECP	National Energy and Climate Plans are the new framework within which EU Member States have to plan, in an integrated manner, their climate and energy objectives, targets, policies and measures for the European Commission. Countries will have to develop NECPs on a ten-year rolling basis, with an update halfway through the implementation period. The NECPs covering the first period from 2021 to 2030 will have to ensure that the Union's 2030 targets for greenhouse gas emission reductions, renewable energy, energy efficiency and electricity interconnection are met.
North Seas offshore grid	NSOG	One of the four priority corridors for electricity identified by the TEN-E Regulation. Integrated offshore electricity grid development and related interconnectors in the North Sea, Irish Sea, English Channel, Baltic Sea and neighbouring waters to transport electricity from renewable offshore energy sources to centres of consumption and storage and to increase cross-border electricity exchange.
North-south electricity interconnections in central eastern and south eastern Europe	NSI East Electricity	One of the four priority corridors for electricity identified by the TEN-E Regulation. Interconnections and internal lines in north-south and east-west directions to complete the EU internal energy market and integrate renewable energy sources.
North-south electricity interconnections in western Europe	NSI West Electricity	One of the four priority corridors for electricity identified by the TEN-E Regulation. Interconnections between EU countries in this region and with the Mediterranean area including the Iberian peninsula, in particular to integrate electricity from renewable energy sources and reinforce internal grid infrastructures to promote market integration in the region.
Power to gas	P2G	Technology that uses electricity to produce hydrogen (Power to Hydrogen – $P2H_2$) by splitting water into oxygen and hydrogen (electrolysis). The hydrogen produced can then be combined with CO_2 to obtain synthetic methane (Power to Methane – $P2CH_4$).
Project (in the TYNDP)		Either a single investment or a set of investments, clustered together to form a project, in order to achieve a common goal.
Project of common interest	PCI	A project which meets the general and at least one of the specific criteria defined in Art. 4 of the TEN-E Regulation and which has been granted the label of PCI project according to the provisions of the TEN-E Regulation.
Put IN one at the Time	PINT	Methodology that considers each new network investment/project (line, substation, PST or other transmission network device) on the given network structure one by one and evaluates the load flows over the lines with and without the examined network reinforcement.
Reference grid		The existing network plus all mature TYNDP developments, allowing the application of the TOOT approach.
Reference capacity		Cross-border capacity of the reference grid used for applying the TOOT/PINT methodology in the assessment according to the CBA.
Scenario		A set of assumptions for modelling purposes related to a specific future situation in which certain conditions regarding electricity and gas demand and supply, infrastructures, fuel prices and global context occur.
Take Out One at the Time	TOOT	A set of assumptions for modelling purposes related to a specific future situation in which certain conditions regarding electricity and gas demand and supply, infrastructures, fuel prices and global context occur.
Ten-Year Network Development Plan	TYNDP	The Union-wide report carried out by ENTSO-E every other year as (TYNDP) part of its regulatory obligation as defined under Article 8, para 10 of Regulation (EC) 714 / 2009.
Top-Down		The "Top-Down Carbon Budget" scenario building process is an approach that uses the "bottom-up" model information gathered from the gas and electricity TSOs. The methodologies are developed in line with the Carbon Budget approach.
Trans-European Networks for Energy	TEN-E	Policy focused on linking the energy infrastructure of EU countries. It identifies nine priority corridors (including 4 for electricity) and three priority thematic areas.

Appendix 2 – List of projects included in the reference grid

The TYNDP2020 reference grid is composed of the existing grid and of the projects listed in the following table. Most of these projects are included in the TYNDP2020 portfolio.

Project ID	Project name	In TYNDP2020 portfolio?
1	RES in north of Portugal	Yes
4	Interconnection Portugal-Spain	Yes
13	Baza project	No
16	Biscay Gulf	Yes
21	Italy-France	No
23	FR-BE I: Avelin/Mastaing-Avelgem-Horta HTLS	Yes
26	Reschenpass Interconnector Project	Yes
28	Italy-Montenegro	Yes
33	Central Northern Italy	Yes
36	Kriegers Flak CGS	Yes
37	Norway – Germany, NordLink	Yes
39	DKW-DE, step 3	Yes
48	New SK-HU intercon. – phase 1	Yes
62	Estonia-Latvia 3rd IC	Yes
75	Modular Offshore Grid (MOG)	No
77	Anglo-Scottish -1	No
78	South West Cluster	Yes
81	North South Interconnector	Yes
85	Integration of RES in Alentejo	Yes
92	ALEGrO	Yes
94	GerPol Improvements	Yes
103	Reinforcements Ring NL phase I	Yes
110	Norway-Great Britain, North Sea Link	Yes
111	3rd AC Finland-Sweden north	Yes
120	MOG II: connection of up to 2 GW additional offshore wind Belgium	Yes
123	LitPol Link Stage 2	Yes
124	NordBalt phase 2	Yes
127	Central Southern Italy	Yes
132	HVDC Line A-North	Yes
134	N-S Western DE_section South	No
135	N-S Western DE_parallel lines	No
138	Black Sea Corridor	Yes
142	CSE4	Yes
144	Mid Continental East corridor	Yes
164	N-S Eastern DE_Central section	No
167	Viking DKW-GB	Yes
172	ElecLink	Yes
173	FR-BE II: PSTs Aubange-Moulaine	Yes
183	DKW-DE, Westcoast	Yes

Project ID	Project name	In TYNDP2020 portfolio?
186	East of Austria	Yes
190	NorthConnect	Yes
191	OWP TenneT Northsea Part 2	No
192	OWP Northsea TenneT Part 3	No
197	N-S Finland P1 stage 2	Yes
200	CZ Northwest-South corridor	Yes
203	Morella-La Plana (previosly Aragón-Castellon)	No
207	Reinforcement Northwestern DE	Yes
208	N-S Western DE_section North_1	Yes
209	Reinforcement Northeastern DE	No
230	GerPol Power Bridge I	Yes
236	Internal Belgian Backbone West: HTLS upgrade Horta-Mercator	No
240	380-kV-grid enhancement between Area Güstrow and Wolmirstedt	No
242	Offshore Wind Baltic Sea (I)	No
245	Upgrade Meeden – Diele	Yes
248	Offshore Wind Baltic Sea (II)	No
254	HVDC Ultranet Osterath to Philipsburg	Yes
255	Connection Navarra-Basque Country	No
258	Westcoast line	Yes
262	Belgium-Netherlands: Zandvliet-Rilland	Yes
266	Swiss Ellipse I	Yes
269	Uprate the western 220kV Sevilla Ring	No
299	SACOI3	Yes
309	NeuConnect	Yes
312	St. Peter (AT) – Tauern (AT)	Yes
313	Isar/Altheim/Ottenhofen (DE) – St.Peter (AT)	Yes
320	Slovenia-Hungary/Croatia interconnection	Yes
336	Prati (IT) – Steinach (AT)	Yes
337	Conneforde-Merzen	No
348	NoordWest380 NL	Yes
350	South Balkan Corridor	Yes
378	Transformer Gatica	Yes
379	Uprate Gatica lines	Yes
1055	Interconnection of Crete to the Mainland System of Greece	Yes
348	NoordWest380 NL	Yes
350	South Balkan Corridor	Yes
378	Transformer Gatica	Yes
379	Uprate Gatica lines	Yes
1055	Interconnection of Crete to the Mainland System of Greece	Yes

Appendix 3 – Candidate capacity increases and cost assumptions

The following capacity increases were proposed to the optimiser. The capacity increases listed in this appendix include projects submitted to the TYNDP 2020 and conceptual increases that do not correspond to existing projects. Cost assumptions are theoretical assumptions that include the assumed costs of reinforcement of internal networks that would be necessary for the cross-border capacity increases. When there are several values on the same border, a sequential consideration of the capacity increases has been proposed to the optimiser.

Border	Capacity (MW)	CAPEX (M€)
AT00-CH00	400	114
AT00-CH00	200	41
AT00-DE00	1500	197
AT00-DE00	460	174
AT00-DE00	100	649
AT00-DE00	1000	206
AT00-DE00	140	44
AT00-ITN1	500	135
AT00-SI00	260	210
AT00-SI00	240	175
BA00-HR00	500	83
BA00-HR00	644	160
BA00-RS00	850	142
BA00-RS00	500	53
BE00-DE00	1000	600
BE00-FR00	1000	90
BE00-LUG1	500	210
BE00-NL00	1000	50
BE00-NL00	1000	185
BE00-NL00	1000	1090
BE00-UK00	1400	900
BG00-RS00	730	77
CH00-DE00	1500	428
CH00-DE00	1000	58
CH00-DE00	600	124
CH00-FR00	1000	35
CH00-FR00	500	60
CH00-ITN1	200	212
CH00-ITN1	200	57
CZ00-DE00	500	321
CZ00-DE00	150	974
CZ00-SK00	500	86
DE00-DKE1	600	460
DE00-FR00	1500	94
DE00-FR00	300	49
DE00-LUG1	1000	166
DE00-NL00	1000	200
DE00-PL00	1500	270
DE00-PL00	400	2597
DE00-SE04	700	660
DE00-SE04	700	660
DKE1-PL00	600	655
ES00-FR00	1500	1170

Border	Capacity (MW)	CAPEX (M€)
ES00-FR00	1500	1470
FI00-SE02	800	488
FR00-IE00	700	930
FR00-UK00	1400	850
HR00-RS00	600	19
HU00-RO00	1117	200
IE00-UKNI	570	396
ITCN-ITCS	1000	564
ITCN-ITN1	1000	564
ITCS-ITS1	200	378
ITCS-ITSI	1000	1135
ITCS-ME00	600	362
ITN1-SI00	1000	755
ITSA-ITSI	1000	1135
ITSI-TN00	600	524
LT00-PL00	700	1907
ME00-RS00	500	83
ME00-RS00	500	53
NL00-UK00	2000	850
RO00-RS00	622	40
SE02-SE03	2000	2281
SE02-SE03	1000	2038
AL00-GR00	500	40
AL00-GR00	1000	45
AL00-GR00	1500	45
AL00-GR00	2000	99
AL00-ME00	500	24
AL00-ME00	1500	35
AL00-MK00	500	48
AL00-MK00	1000	67
AL00-MK00	1500	114
AL00-RS00	500	25
AL00-RS00	1000	33
AL00-RS00	1500	58
AT00-CH00	1000	582
AT00-CH00	2000	1054
AT00-CH00	3000	2620
AT00-CH00	4000	6221
AT00-CZ00	1000	454
AT00-CZ00	1500	842
AT00-DE00	1000	3000
AT00-HU00	1000	547
AT00-HU00	2000	1215

Border	Capacity (MW)	CAPEX (M€)
AT00-ITN1	1000	1305
AT00-SI00	500	127
AT00-SI00	1000	688
AT00-SK00	1000	456
BA00-HR00	500	192
BA00-HR00	1000	384
BA00-ME00	500	58
BA00-ME00	1000	116
BA00-ME00	1500	174
BA00-ME00	2000	225
BA00-RS00	500	45
BE00-DE00	1000	750
BE00-DE00	2000	1450
BE00-DE00	3000	2250
BE00-FR00	1000	236
BE00-FR00	2000	371
BE00-FR00	3000	749
BE00-NL00	1000	890
BE00-NL00	2000	1960
BE00-UK00	1000	1250
BE00-UK00	2000	2750
BG00-GR00	500	65
BG00-GR00	1000	95
BG00-GR00	1500	150
BG00-GR00	2000	220
BG00-MK00	500	51
BG00-MK00	1000	83
BG00-MK00	1500	147
BG00-RO00	500	147
BG00-RO00	1000	318
BG00-RO00	1500	430
BG00-RO00	500	75
BG00-RO00	1000	117
BG00-RO00	1500	192
BG00-RS00	500	51
BG00-TR00	500	58
BG00-TR00	1000	116
BG00-TR00	1500	174
CH00-DE00	1000	1000
CH00-DE00	2000	2000
CH00-FR00	1000	550
CH00-FR00	2000	1100
CH00-ITN1	1000	850

Border	Capacity (MW)	CAPEX (M€)
CY00-GR03	500	1000
CY00-GR03	1000	1700
CY00-GR03	1500	3000
CY00-GR03	2000	4300
CZ00-DE00	1000	1450
CZ00-DE00	2000	2900
CZ00-DE00	3000	4340
CZ00-DE00	3500	5800
CZ00-PL00	500	650
CZ00-PL00	1000	780
CZ00-PL00	1500	1170
CZ00-SK00	500	293
CZ00-SK00	1000	328
DE00-DKE1	500	460
DE00-DKW1	1000	2430
DE00-DKW1	2000	2650
DE00-FR00	1000	1000
DE00-FR00	2000	2000
DE00-FR00	3000	3000
DE00-LUG1	1000	350
DE00-NL00	500	1850
DE00-NL00	1000	2075
DE00-NL00	2000	2650
DE00-NL00	3000	3225
DE00-NOS0	1000	3500
DE00-NOS0	2000	4300
DE00-PL00	500	422
DE00-PL00	1000	542
DE00-PL00	2000	662
DE00-PL00	3000	782
DE00-SE04	500	660
DE00-SE04	1000	1320
DE00-UK00	500	3100
DE00-UK00	1000	3600
DE00-UK00	2000	4400
DKE1-PL00	500	571
DKE1-PL00	1000	1242
DKE1-PL00	2000	2484
DKE1-PL00	3000	4476
DKE1-SE04	500	150
DKE1-SE04	1000	300
DKE1-SE04	1500	450
DKW1-NL00	1000	1550

Border	Capacity (MW)	CAPEX (M€)
DKW1-NL00	2000	3100
DKW1-NOS0	500	600
DKW1-NOS0	1000	850
DKW1-NOS0	1500	1150
DKW1-NOS0	2000	1500
DKW1-UK00	1000	1720
DKW1-UK00	1500	2725
DKW1-UK00	2000	3266
EE00-FI00	500	370
EE00-FI00	1000	740
EE00-FI00	1500	1110
EE00-FI00	2000	1480
EE00-LV00	500	120
EE00-LV00	1000	250
EE00-LV00	1500	380
EE00-LV00	2000	510
ES00-FR00	2000	2500
ES00-FR00	4000	5700
ES00-PT00	500	61
ES00-PT00	1000	87
ES00-PT00	1500	120
ES00-PT00	500	87
ES00-PT00	1000	90
ES00-PT00	1500	114
ES00-PT00	500	157
ES00-PT00	1000	233
ES00-PT00	1500	268
ES00-PT00	500	176
ES00-PT00	1000	295
ES00-PT00	1500	331
FI00-NON1	500	500
FI00-NON1	1000	1140
FI00-NON1	1500	1710
FI00-NON1	2000	2280
FI00-SE01	1000	915
FI00-SE01	2000	2196
FI00-SE03	1000	1830
FI00-SE03	2000	4392
FR00-IE00	700	1000
FR00-ITN1	1000	1260
FR00-ITN1	2000	2520
FR00-UK00	1400	906
FR00-UK00	3400	2306

Border	Capacity (MW)	CAPEX (M€)
GR00-ITS1	1000	1200
GR00-MK00	500	5
GR00-MK00	1000	39
GR00-MK00	1500	260
GR00-TR00	500	87
GR00-TR00	1000	92
GR00-TR00	1500	92
HR00-HU00	500	187
HR00-HU00	1000	307
HR00-HU00	1500	436
HR00-RS00	500	13
HR00-RS00	1000	58
HR00-SI00	500	53
HR00-SI00	1000	100
HR00-SI00	1500	144
HR00-SI00	2000	200
HU00-RO00	500	375
HU00-RO00	1000	600
HU00-RS00	500	60
HU00-RS00	1000	170
HU00-RS00	1500	342
HU00-SI00	500	124
HU00-SI00	1000	247
HU00-SI00	1500	371
HU00-SI00	2000	500
HU00-SK00	500	196
HU00-SK00	1000	378
HU00-SK00	1500	567
IE00-UK00	500	521
ITCS-ME00	1000	1000
ITN1-SI00	1000	750
ITSI-MT00	500	500
ITSI-MT00	1000	1000
ITSI-MT00	1500	1500
ITSI-MT00	2000	2000
LT00-LV00	1000	500
LT00-LV00	2000	1000
LT00-LV00	3000	1500
LT00-LV00	4000	2000
LT00-PL00	500	970
LT00-PL00	1000	1400
LT00-PL00	2000	2800
LT00-SE04	1000	1800

Border	Capacity (MW)	CAPEX (M€)
LT00-SE04	1000	1800
LT00-SE04	1000	1800
LT00-SE04	1000	1800
ME00-RS00	500	18
MK00-RS00	500	14
MK00-RS00	1000	47
MK00-RS00	1500	54
NL00-NOS0	1000	2100
NL00-NOS0	2000	4200
NL00-NOS0	3000	6300
NL00-NOS0	4000	8400
NL00-UK00	1000	1135
NL00-UK00	2000	2270
NOM1-SE02	500	250
NOM1-SE02	1000	500
NOM1-SE02	1500	750
NON1-SE01	500	250
NON1-SE01	1000	500
NON1-SE01	1500	750
NON1-SE02	500	250
NON1-SE02	1000	500
NON1-SE02	1500	750
NOS0-SE03	500	250
NOS0-SE03	1000	500
NOS0-SE03	1500	750
NOS0-UK00	500	1015
NOS0-UK00	1000	1530
NOS0-UK00	1500	1945
NOS0-UK00	2000	2350
PL00-SE04	500	700
PL00-SE04	1000	1400
PL00-SE04	1500	2100
PL00-SK00	500	550
PL00-SK00	1000	551
PL00-SK00	1500	827
RO00-RS00	500	57
RO00-RS00	1000	169
RO00-RS00	1500	208
RO00-RS00	2000	278
UK00-UKNI	500	782
UK00-UKNI	1000	822
UK00-UKNI	1500	1429
UK00-UKNI	2000	1488

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