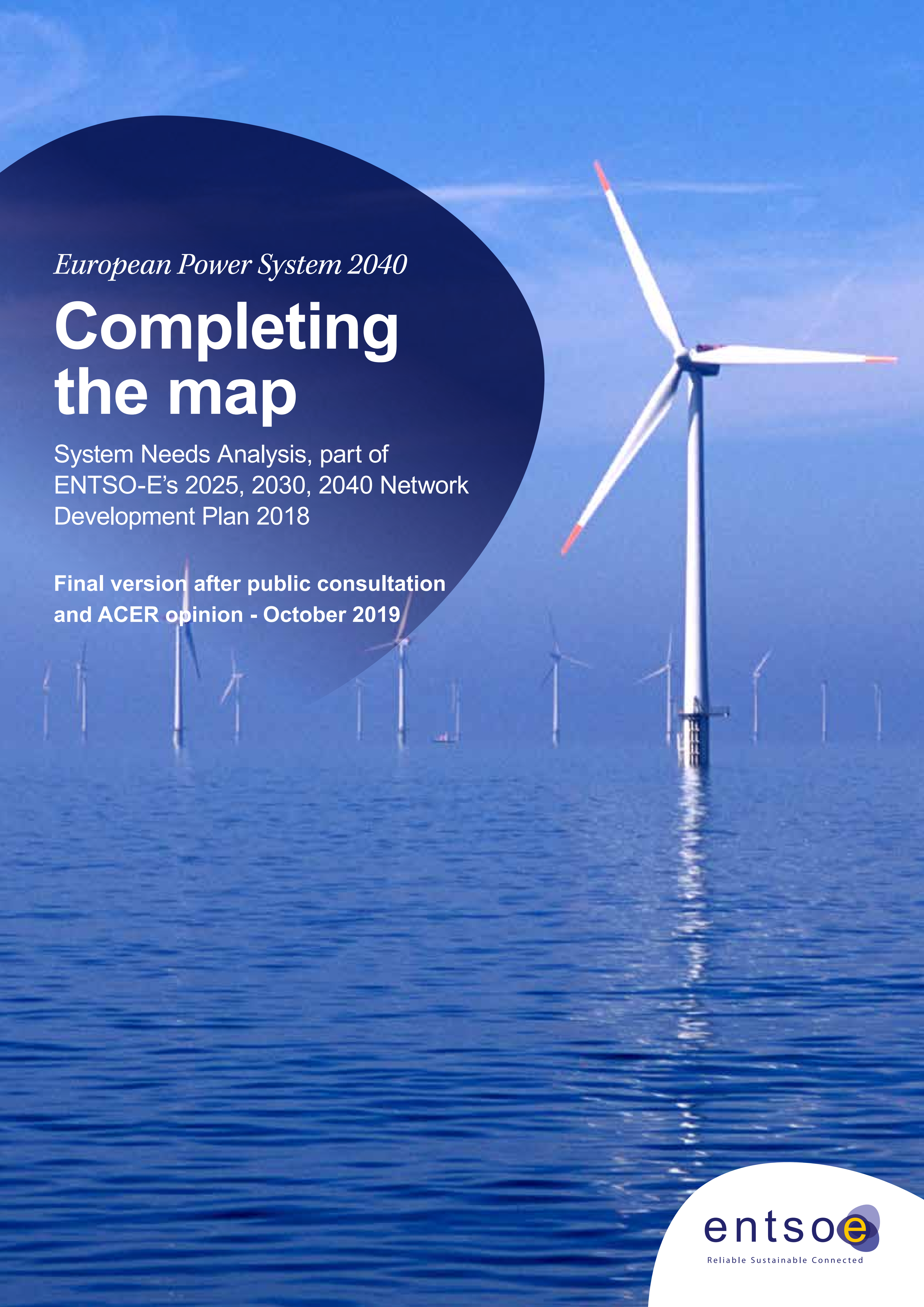
European Power System 2040

Completing the map

System Needs Analysis, part of ENTSO-E's 2025, 2030, 2040 Network Development Plan 2018

Final version after public consultation and ACER opinion - October 2019



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Reliable Sustainable Connected

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Foreword

Power networks facilitating a system of systems

The power system in Europe is changing rapidly. While it was originally designed on the basis of centralised predictable generation ensuring steady power flows, it has progressively evolved to integrate more decentralised and variable renewable energy sources. Today almost one-third of the power generation mix is provided through variable renewables in Europe, even though the proportion can vary greatly from country to country.

Renewables, particularly photovoltaics and onshore wind, have introduced new challenges for power system operators that have to co-ordinate distributed, small-scale generation assets across their networks.

In fact, the architecture of the European power system is evolving into an architecture whereby centralised and decentralised coexist. New actors and new services are needed to optimise flexibility at local, national, regional and European levels. Network operators, from transmission and distribution, have a key role in facilitating the orchestration of new transactions over the whole value chain.

It is clear that we are evolving towards a system of systems. The 'Fourth Industrial Revolution' increases interfaces, interactions and transactions at every stage of the system and between systems. Power networks are central in this evolution, and will remain a fundamental pillar of this transformation where sectors will need to further couple across electricity, gas, heating, transport and digital.

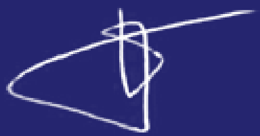
The power networks that have been built progressively in Europe since the early days of electricity have to adapt to this paradigm shift. New hardware and software are needed to enable new interactions and to provide the capacity to flow competitive renewables from north to south Europe, ultimately bridging offshore wind from the Nordic countries with photovoltaics from southern countries.

This report provides a quantified overview of the needs of the power system of tomorrow, looking through to the 2040 time horizon. It illustrates why constructing more physical lines is so crucial and what the cost of doing nothing would be. It also insists on innovation and the development of new tools and principles in network optimisation to guarantee a high level of security of supply, integrate more renewables, and support more and more cross-border electricity exchanges.

On this specific topic of cross-border trade, closer interaction between network operators, policymakers and regulators at the regional level is highly desirable so as to debate important questions and choices impacting citizens.

ENTSO-E is notably working towards developing a vision for how both market and operation should be updated, hoping to contribute further to finding collective solutions to the issues highlighted in this report.

As this publication shows, together with its members, ENTSO-E is committed to developing the power system that will support Europe's competitiveness and sustainability and will guarantee a safe supply of power to Europeans for the decades to come.



Laurent Schmitt
ENTSO-E *Secretary General*

Section 1

Executive summary

What 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 climatic agenda? Furthermore, what would be the cost of not having the right grid by 2040?

ENTSO-E's long-term pan-European grid planning (the biennial 10-year network development plan or TYNDP) 2016 presented a plan for the European electricity grid for 2030. The E-HIGHWAY 2050 European research project explores the need for grids in a near-to-full decarbonised economic context.

The present report is looking at 2040. Very high levels – up to 75% of the total demand – of renewable energy sources (RES) will be reached, and European countries will need to rely more than ever on each other through cross-border exchanges. This means more capacity at borders, which goes hand in hand with reinforcing national grids. This report and the six Regional Investment Plans it accompanies present how to complement the power-system maps by 2040 in the most efficient way.

The right set of increases in the transmission capacity between and within European countries could indeed reduce market prices in most of the countries, strengthen security of supply (SoS) and allow for the integration of a high share of RES in the system. Such increases could enable countries momentarily producing more energy than they need, as in the case of high wind or solar, to export their production. Whereas, at other times, they could import cheap wind or solar energy. Overall, this means optimising the use of renewable energy and of generation resources in Europe so that security of supply can be maintained at the best cost for all Europeans.

Completing the map

In the context of the mid- to long-term pan-European planning, but also research and development activities, ENTSO-E has developed three 2040 scenarios describing how Europe's future energy could look. The scenarios consider a very centralised, digitalised system as well as one driven by strong international cooperation or rather by a continuation of the present policies. In all scenarios, European climate targets are met or exceeded.

The present analyses of pan-European electricity system needs is based on those scenarios which have been widely consulted on and co-created with ENTSOG so as to maximise the synergies between the two networks. This document and the six Regional Investment Plans, which all provide in-depth analysis of the studies presented in this report, as well as specific regional elements, are part of the TYNDP 2018 package. The scenarios are thus ambitious and offer a wide spectrum of potential energy futures for Europe. Thanks to this strong basis, the present report assesses where transmission capacity should increase, and by how much, by taking into account policy – such as cheaper electricity for consumers – and environmental objectives. It will shed some light on increasing challenges in terms of real-time system management in the 2040 electricity landscape.

This report aims to offer the most reliable assessment of:

— pan-European network needs
— the impact and needs in regions
— where grid projects should be considered

but also
— potential policy requirements and/or adjustments
— future technical challenges to be addressed.

Preparing for the 2040 future system

A number of additional capacity increases, and thus new projects, will be necessary in the future beyond the TYNDP 2016 project portfolios.

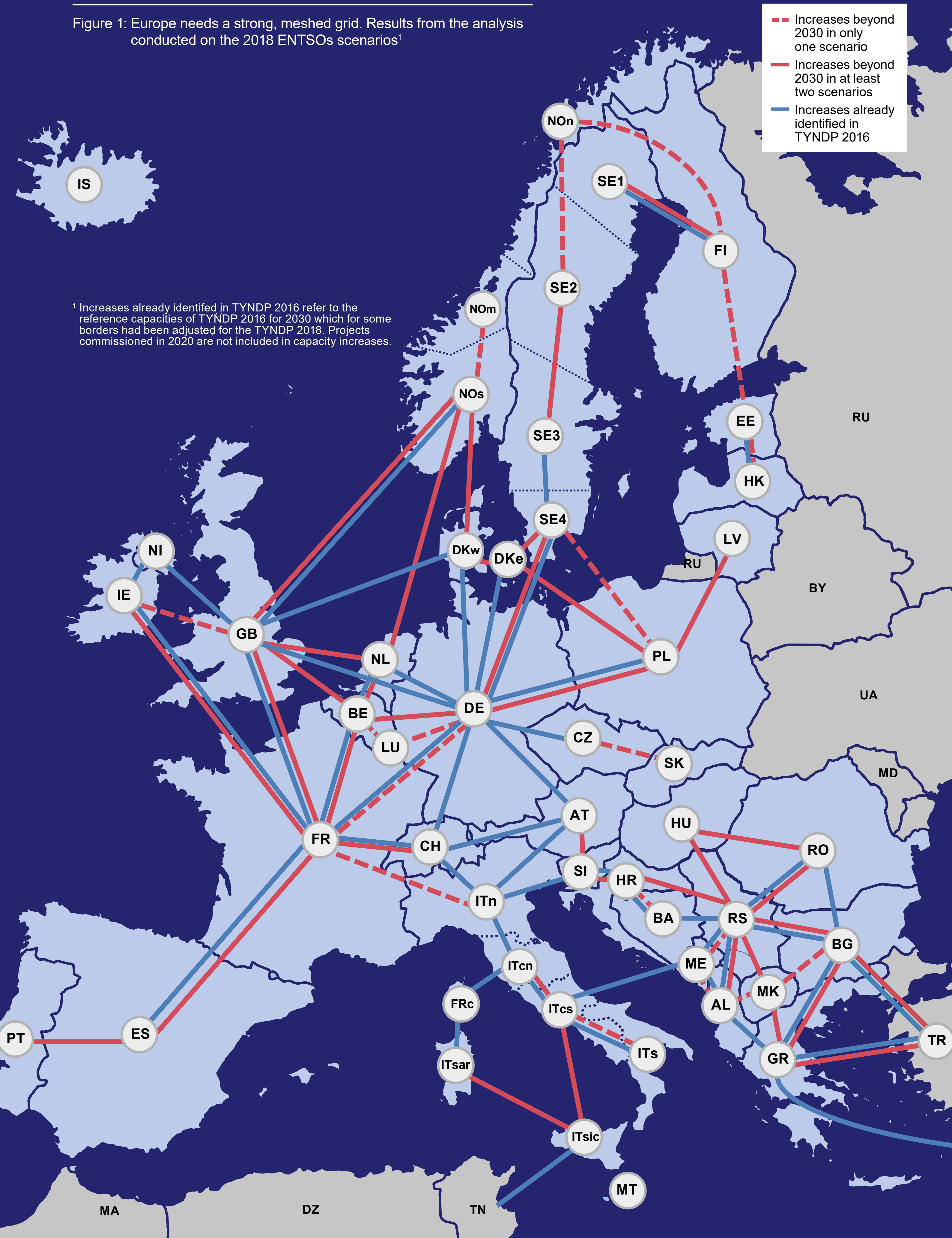
If these additional interconnector reinforcements were developed they would:

— reduce market prices on average over a year
— decrease curtailed energy in countries with significant levels of renewable energy installed, and
— increase the security of supply in scenarios with a low number of conventional power plants (for example, nuclear and coal) in operation compared to the situation today.

But interconnection is not enough. For the benefits of the interconnector reinforcements to materialise and the integration of renewable energy sources at large to be sustained, internal grid reinforcements will also be needed to operate the system in a safe and efficient way.

The new conditions by 2040 will also make it more and more difficult for system operators to manage the system in real time, as large power flows will need to travel across Europe, and large controllable power plants are being replaced by small and distributed sources. This will require innovation in grids – notably ICT/ digital solutions – but also new market design, policy and regulatory coordination to increase flexibility in the system.

Figure 1: Europe needs a strong, meshed grid. Results from the analysis conducted on the 2018 ENTSOs scenarios[1]



[1] Increases already identifed in TYNDP 2016 refer to the reference capacities of TYNDP 2016 for 2030 which for some borders had been adjusted for the TYNDP 2018. Projects commissioned in 2020 are not included in capacity increases.

1.1

Summary of conclusions

New investment needed after 2030

- There will be a need for increased transmission capacity in some places to make the system work in 2040. The interconnection projects currenty under development and identified in TYNDP 2016 will need to be completed by new entries responding to these needs in future editions of the TYNDP.
- New interconnection needs have been identified across and between all regions, largely due to the increasing levels and use of renewable resources to supply all areas of the European grid.
- To deliver the new necessary levels of interconnections, a high level of internal reinforcements of the grid will also be necessary in most European countries.

The high cost of no grid

- Overall benefits for Europeans of a fit-forpurpose network (both financially, and to ensure continued access to electricity and enable climate objectives) far outweigh the necessary efforts which will need to be mobilised in the coming decades for its realisation.
- A lack of new investments by 2040 would hinder the development of the integrated energy market and lead to a lack of competitiveness. In turn, this would increase prices in electricity markets leading to higher bills for consumers. By 2040, the 'no grid' extra bill (€43 billion a year in the average case) would be largely above the expected cost of the new grid (€150 billion in total in the TYNDP 2016 plus internal reinforcements, 25% discount rate).
- A lack of investments will affect the stability of the European grid and could, in some regions, threaten the continued access to electricity which also has a cost for society.
- All scenarios considered show that without grid extension, Europe will not meet its climate targets.

Policy and technical challenges foreseen when integrating renewables

- Operating in real time, by 2040 the grid will be made more difficult by the large flows of electricity travelling across Europe, and the replacement of large generators by non-controllable, distributed RES.
- System operators will need new solutions to ensure frequency and voltage stability, leading to new responsibilities for market participants.
- The challenges not only require technological solutions, but also a higher level of regulatory and policy coordination, as well as innovation in market design to increase flexibility in the system.

Section 2

Introduction

ENTSO-E has investigated pan-European system needs based on future scenarios as part of its European studies.

As the future could develop in many different ways, ENTSO-E decided to investigate three different 2040 scenarios, namely Global Climate Action, Sustainable Transition and Distributed Generation. These scenarios were co-created with ENTSOG (European Network of Transmission System Operators for Gas) and other stakeholders to ensure the most accurate and exhaustive visions for the future. The scenarios are described in more detail in sections 6 and in the separate Scenario Report[2].

Because of their largely consulted and co-created nature, ENTSO-E scenarios for 2040 offer a solid basis to identify future interconnection and system needs.

The current report focuses on three main drivers for increasing transmission capacity: social economic welfare, security of supply, and European climate goals. Then, according to the three scenarios, ENTSO-E analysed where an increase in capacity was needed. The same approach was used in the Regional Investment Plans – jointly released – so as to ensure consistency of the results at regional and pan-European level.

TYNDP lists projects that will support meeting the European system needs by 2040 and, as usual, will provide a cost-benefit analysis of each project based on the needs identified here.

[2] https://www.entsoe.eu/Documents/TYNDP%20documents/14475_ENTSO_ScenarioReport_Main.pdf

Section 3

New capacity increases

Beyond the portfolio of projects in the previous TYNDP, greater integration of markets through new interconnectors is needed and could provide benefits financially, environmentally and in terms of security of supply.

3.1

Cross-border capacity increases

Methodology: Identifying capacity increases
In order to go beyond the learning of the TYNDP published in 2016 (focusing on 2030 scenarios), ENTSO-E analysed which new capacity increases would be necessary by 2040.

To do so, ENTSO-E determined, for three distinct 2040 scenarios, which European borders presented the highest economic gains when equipped with an additional interconnector (using standard development costs for each border). This operation was repeated until no new profitable route could be identified. Following the economic analysis, ENTSO-E tested two additional criteria in order to identify borders where additional capacity was needed for non-economic reasons (integration of RES and security of supply).

The methodology is presented in section 7 of this document.

The result of this analysis is a set of proposed capacity increases per European border, and an indication of the need they respond to (economic, security of supply or RES).

All European regions are concerned by the transformation of the energy landscape. The analysis therefore showed a need for new projects in each European region. Many of the necessary capacity increases are valid in more than one scenario, and justified by more than one driver (socio-economic welfare – SEW, RES and SoS).

Each of the capacity needs identified will require further investigation. It is also certain that the proposed set of capacity increases does not represent the only solution, as other combinations of capacity increases could also address the same needs.

Furthermore, the value for society of a capacity increase can only be assessed considering their interaction with each other. A change in the sequence of capacity increases could therefore have led to another valid end result. In addition, the phenomenon studied in this report could, and will also have to, be addressed through new market designs and the development of storage and smart grids (although these elements are already ambitiously represented within the scenarios, and would therefore necessitate an exceptional and unforeseen development to efficiently address the needs described in this report).

The following three maps show the specific reason for which an increase has been identified in every scenario.

Subsequent to the outcomes of this report, it is envisaged that both transmission system operators (TSOs) and other project promoters will consider and appraise whether a project is viable (in coordination with the relevant TSOs to which they are connecting), considering in more detail where exactly these projects could be built using which technology (AC or DC, voltage level, etc.). Any resulting proposed projects submitted will be shown against the associated needs in the TYNDP 2018 (or later TYNDPs) to perform the cost-benefit analysis (CBA) and ensure that the project is robust against different realistic scenarios.

Figure 2: Summary of identified border increases in 2040[3]

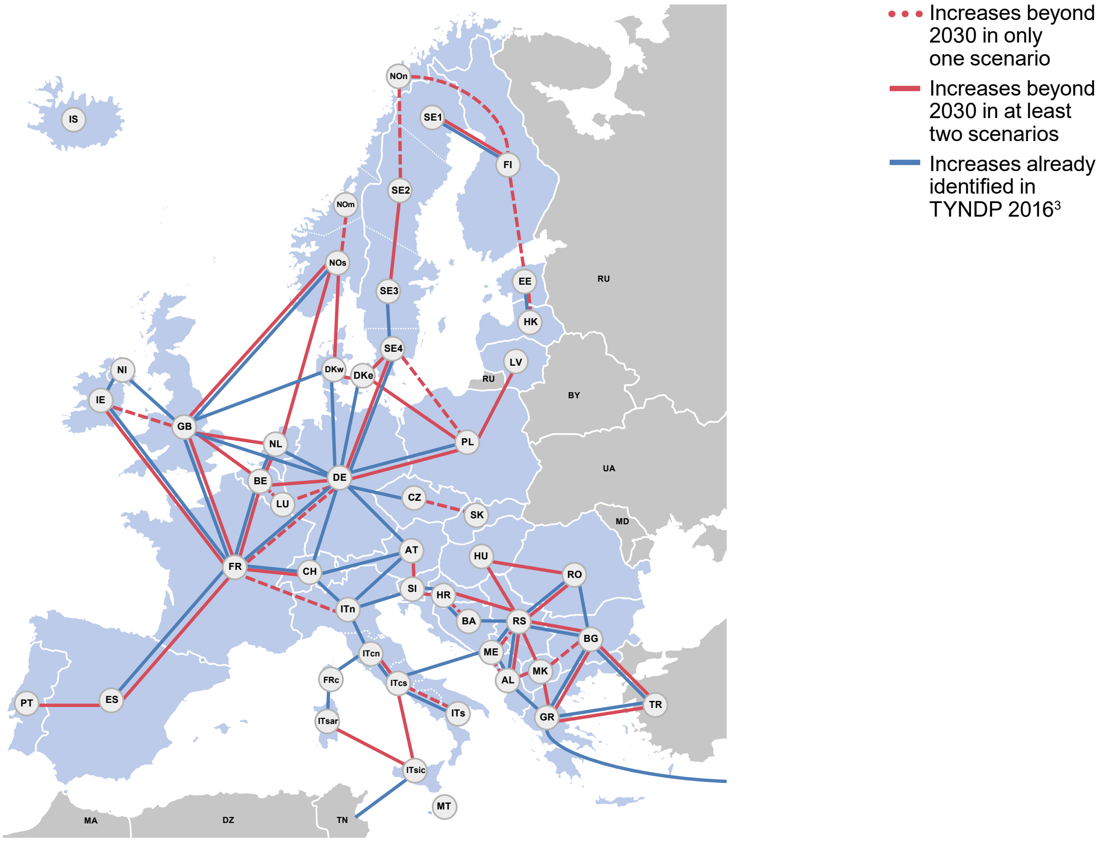
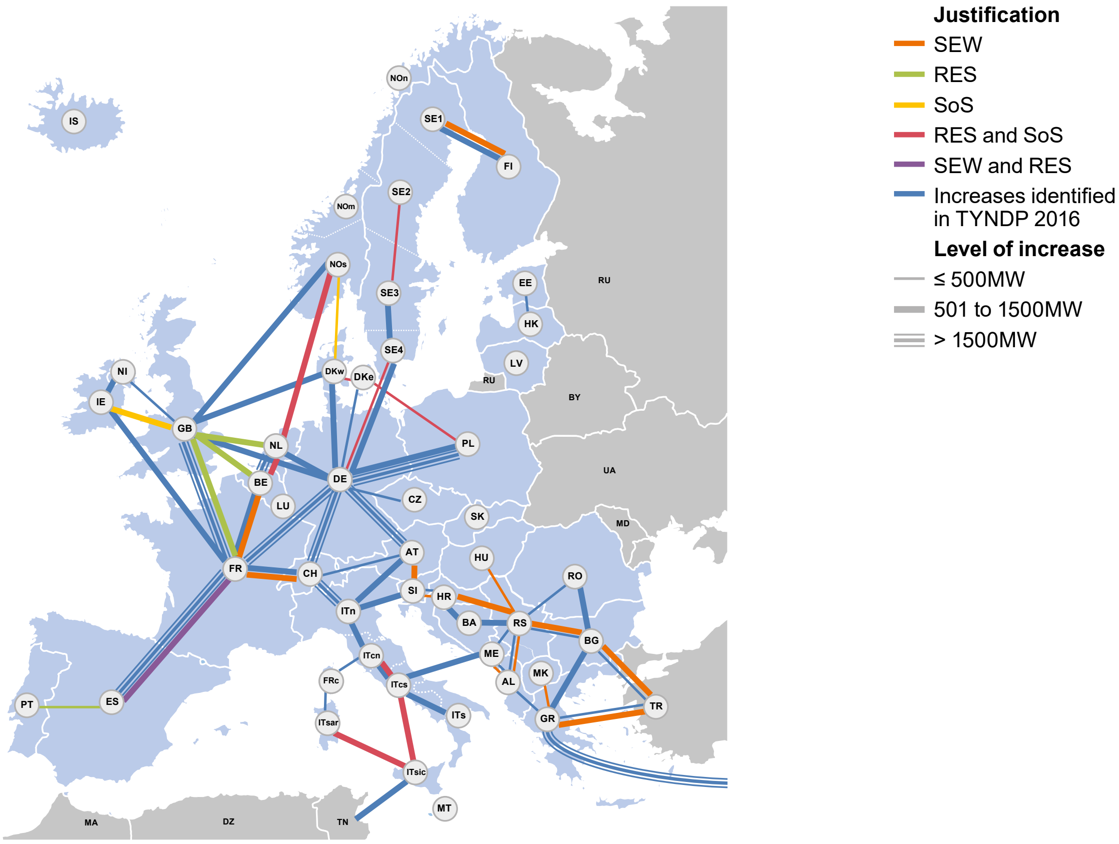


Figure 3: Justification of increases from ST 2040 on top of confirmed increases from previous TYNDP



[3] "Increases already identified in TYNDP 2016" refers to the reference capacities of TYNDP 2016 for 2030 which had been adjusted for TYNDP 2018 for some borders. Projects commissioned in 2020 are not included as capacity increases.

Figure 4: Justification of increases from DG 2040 on top of confirmed increases from previous TYNDP[3]

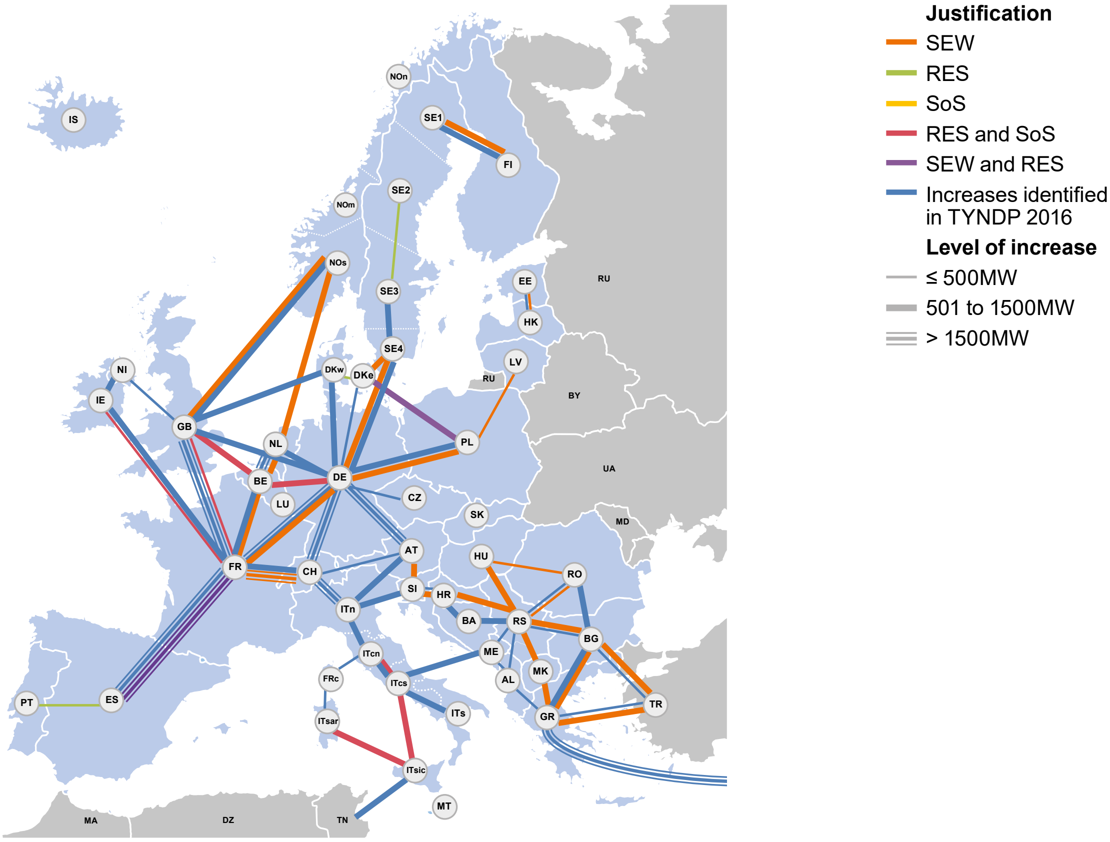
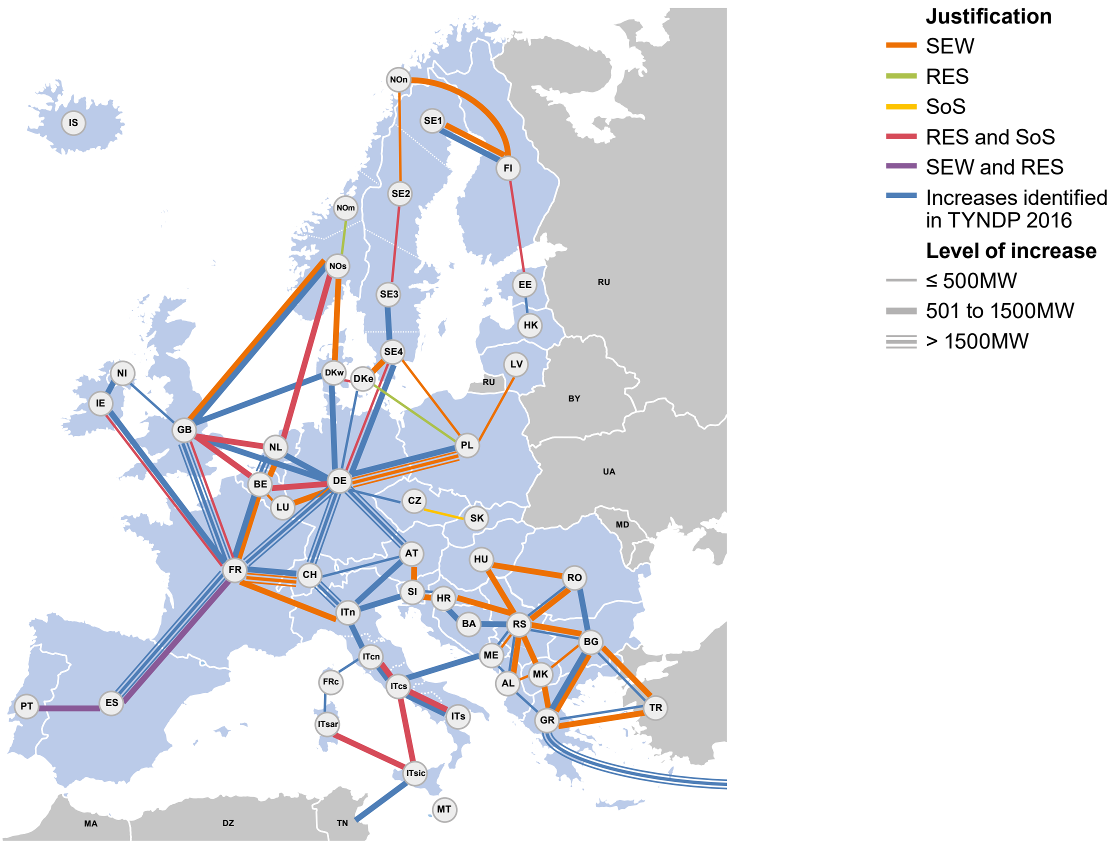


Figure 5: Justification of increases from GCA 2040 on top of confirmed increases from previous TYNDP



3.2

Internal reinforcements

Reaching the level of cross-border exchanges and distributed production envisaged in the different scenarios will create new stress on the European national grid, and will stimulate new needs for internal reinforcements.

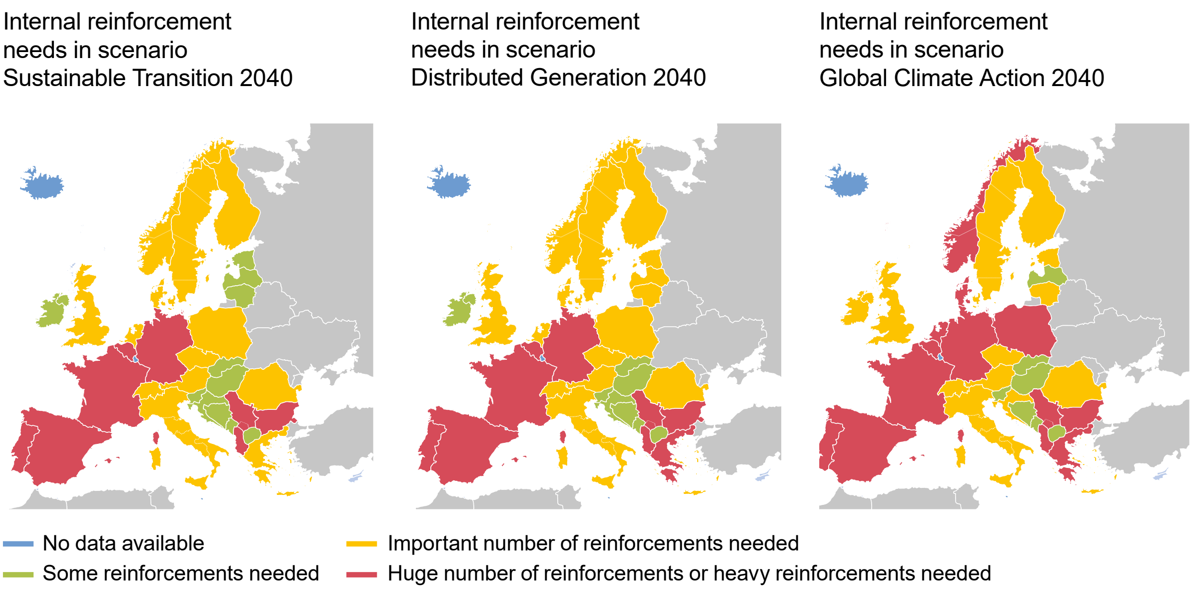
Figure 6 shows these internal reinforcement needs for all three scenarios without any additional cross-border capacities.

New needs for cross-border capacity increases were identified for each scenario. These increases would lead to additional pressure on the internal network grids, shown in Figure 7. Both maps (Figures 6 and 7 for each scenario) together show the total needs to enable every 2040 scenario, including the scenario grid identified[4].

For example, a country shown in red in Figure 6, will need to realise internal reinforcements of the grid to enable the scenarios without additional cross-border capacities. Once this has been done, these reinforcements may actually also facilitate the new cross-border flows highlighted resulting from the new capacity increases identified in this report. In such a situation, a country can appear in green in Figure 7 while it appeared in red in Figure 6. While many of the needs shown in Figures 6 and 7 will be addressed by projects within the TYNDP 2018, supplementary projects may be required which will be channelled into future TYNDPs.

100%
Both maps together show the total needs to enable every 2040 scenario.

Figure 6: Internal reinforcements needed to enable the scenarios without additional cross-border capacities



As a result of the Identification of System Needs (IoSN) studies, needs for cross-border capacity increases were identified for each scenario (see previous section). These increases lead to additional pressure on the internal network grids. Both figures (Figures 6 and 7) together show the total needs to enable every 2040 scenario, including the identified scenario grid[4].

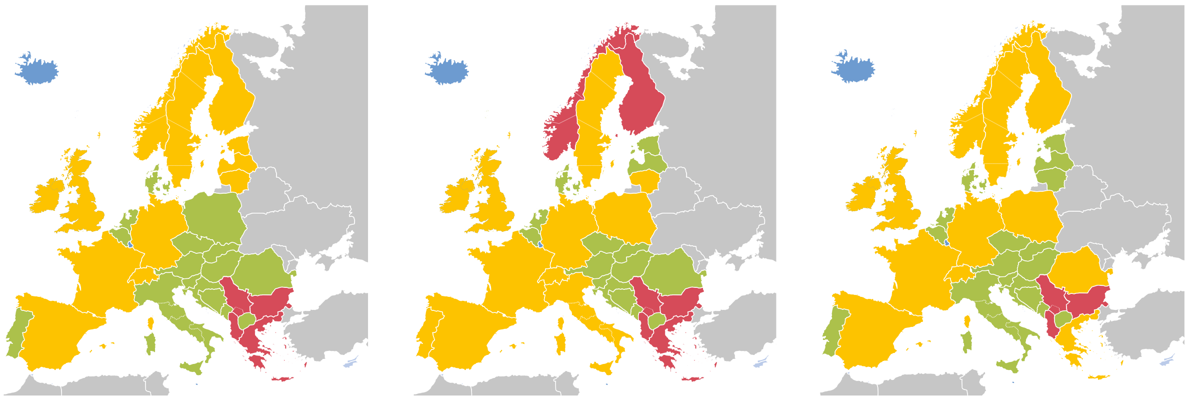
[4] The identified cross-border capacities of the scenario grids can be found in the appendix.

Figure 7: Internal reinforcements needed to accommodate the additional cross-border capacity needs in the scenarios

Additional internal reinforcement needs following cross-border capacity increases identified in scenario Sustainable Transition 2040

Additional internal reinforcement needs following cross-border capacity increases identified in scenario Distributed Generation 2040

Additional internal reinforcement needs following cross-border capacity increases identified in scenario Global Climate Action 2040



- No data available
- Some reinforcements needed
- Important number of reinforcements needed
- Huge number of reinforcements or heavy reinforcements needed

Section 4

The costs of no grid in the 2040 electricity system

It will be necessary to deliver additional investments in the transmission infrastructure beyond the already significant project portfolio of TYNDP 2016, as shown in the previous section. This massive undertaking will require strong and coordinated political, technical and financial efforts throughout Europe for decades to come.

The costs of developing the grid are, however, far smaller than the economic, security of supply and environmental costs incurred if the capacity of the transmission grid was not increased.

“Energy should flow freely across the EU – without any technical or regulatory barriers. Only then can energy providers freely compete and provide the best energy prices, and can Europe fully achieve its renewable energy potential.”

Vice-President Maroš Šefčovič

Methodology: the no-grid 2040 scenario
What would be the consequences of no (additional) grid for Europeans by 2040? To answer this question, we created no-grid versions of each of the 2040 ENTSOs scenarios.

These scenarios keep the generation portfolio and the demand levels of original scenarios, but use a 2020 version of the grid (projects which will be operational by 2020 are in the final stages of their delivery and therefore rather certain to happen).

Testing these scenarios and comparing the results to simulations of original scenarios allows the reader to grasp concretely the value of the overall investment portfolio, rather than incremental benefits of additional capacity increases.

In this chapter, average results for the three original and no-grid scenarios are presented in order to increase readability. Simulations have been performed using three different sets of climatic conditions. These variations are also incorporated into the average results presented in this section. Full results are available in the Technical Appendix.

4.1

Fragmented markets and higher bills

No new grid beyond 2020 would directly hit the European objective of a well-integrated European energy market.

The severe limitation that this would place on cross-border exchanges, coupled with a heterogeneous distribution of renewables across Europe, would lead to important splits between regional market prices, with price differences at the borders going up by 600% in the worst cases. This means that the cohesion of the European single market would be harmed by vastly different electricity costs between neighbouring countries.

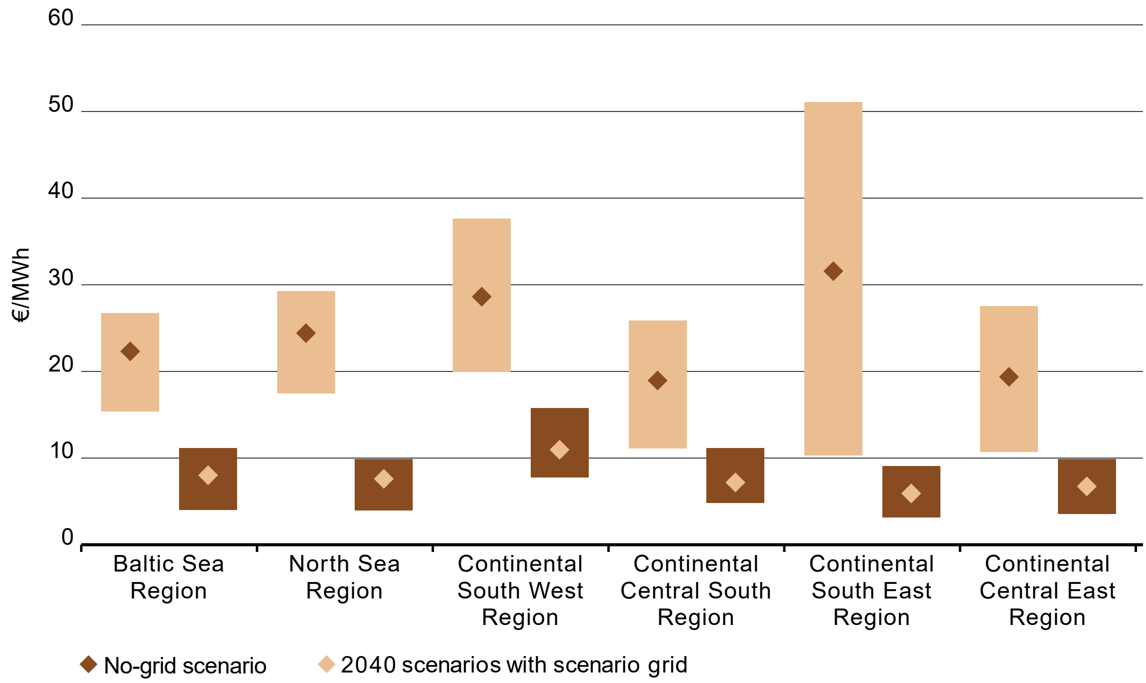
The following chart shows ranges and the average hourly marginal cost differences between neighbouring countries for ENTSO-E's six regional groups. In general, marginal cost differences at borders are highest in the Global Climate Action scenario (GCA) and lowest in the Sustainable Transition scenario (ST) (see full figures in the Technical Appendix). This is due to the fact that the GCA and ST scenarios are based on the highest and lowest growth of renewable resources.

€+43 billion/year

Not reinforcing the transmission grid at borders and within countries would increase the total European market value by €43 billion per year by 2040 in an average case. This is more than three times the €12 billion per year Europeans need to invest to reinforce the grid, according to the TYNDP 2016.

Figure 8: Range and average annual marginal cost differences

Range and average of all scenarios and climate years



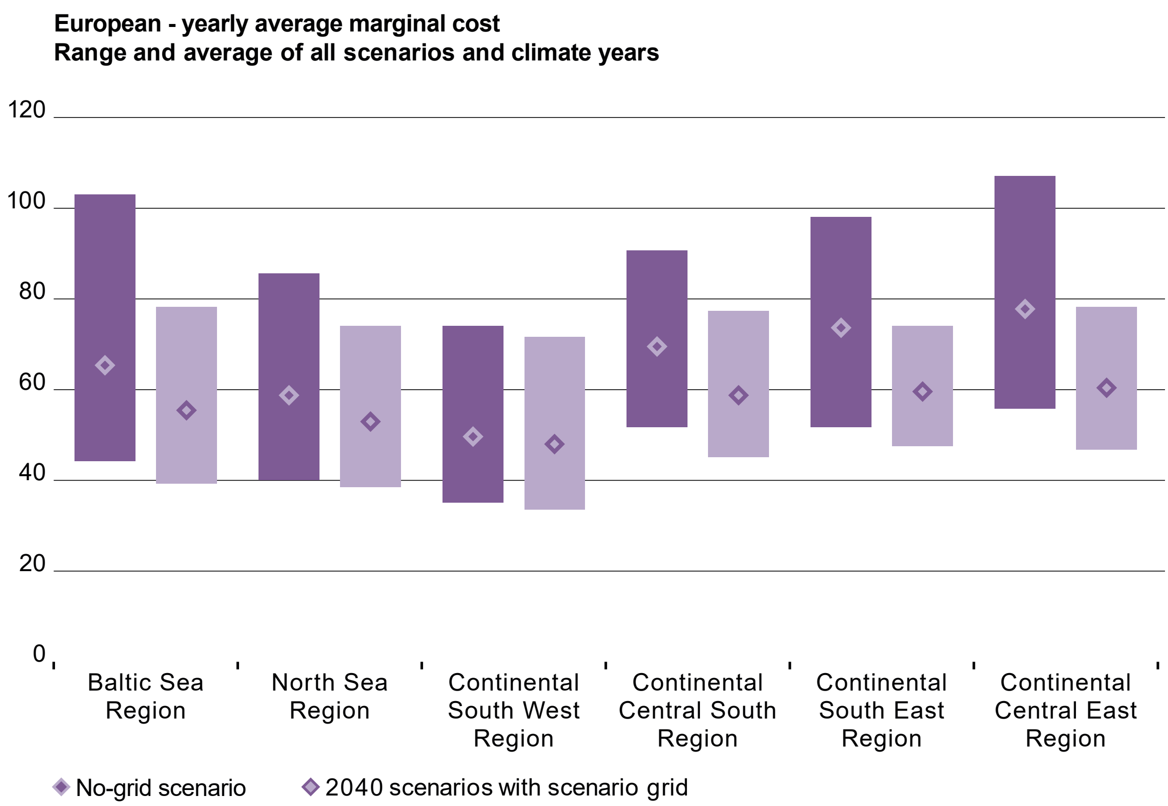
Bringing the electricity markets differences to zero between neighbouring countries is not an objective in itself, as local conditions and grid development costs must be taken into account. However, in a less integrated market system the power is less efficient, meaning that power cannot flow from lower-cost areas to more expensive ones. Thus, fragmented markets lead to a rise in marginal prices, with a direct impact on consumers' electricity bills.

As a consequence of the market splits, all regions see a rise in their regional marginal price average in the no-grid case, from +1.4 to +17.4 €/ MWh (+3% to +29% depending on regions) (Figure 9). Considering the overall amount of electricity generated by 2040, this corresponds to billions of euros a year which will eventually be paid by European consumers.

Figure 10 shows these marginal price spreads in each region (the price at which electricity is traded on the market).

This reduction is more significant in the Central South East region (around 26 €/MWh reduction) due to the increase in power flows from the eastern part of the region, with a higher RES production portfolio in 2040, to the western part where the generation portfolio is dominated mainly by fossil fuel. Furthermore, after 2020, Cyprus will be part of the interconnected system which will contribute to the reduction of marginal cost differences in the whole region.

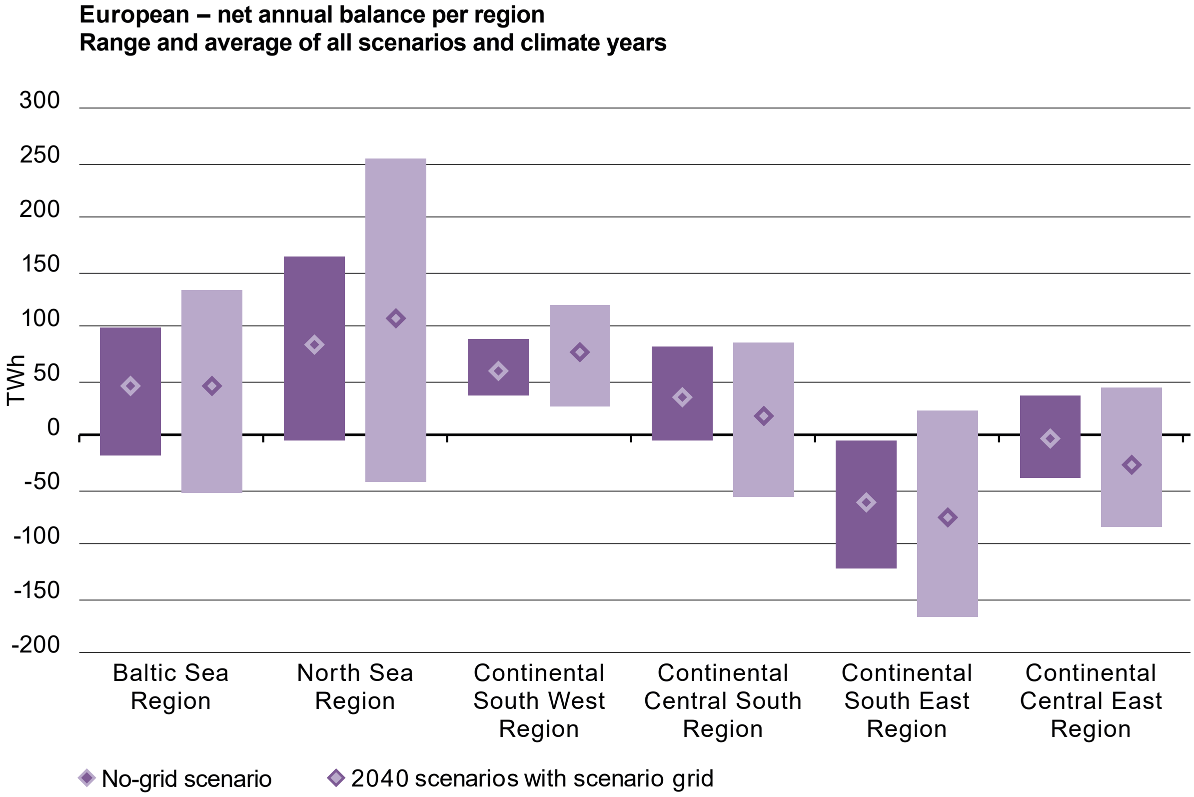
Figure 9: Range and average annual marginal cost per regional group



The enhanced grid leads to a much greater level of power transfer between countries (Figure 10) as this network is used to trade more efficient power. This is a good indicator that the additional grid is actually supportive of trade throughout Europe and a more efficient use of the generation portfolio.

The North Sea region experiences the greatest increment in cross-border exchanges as well as having the greatest difference in net balances between scenarios. In this region, the generation production mix in Norway and Great Britain is very dependent on the set of climatic conditions, which leads to a high variation in net balances between scenarios. All the regions are net exporters except Central South East and Continental Central East[5].

Figure 10: Net annual region balance in 2040, depending on assumed grid status



[5] Many countries are part of several regions and have therefore been included several times in the balance figures.

4.2

Threatening reliable access to electricity

No grid beyond 2020 would also have a tangible impact on Europe's economy and Europeans' quality of life by putting at risk the reliability of access to electricity. If renewable energy sources and new electricity uses keep growing as foreseen, failure to deliver on transmission investments would lead to unacceptable and never before seen levels of business inoperability or even blackouts.

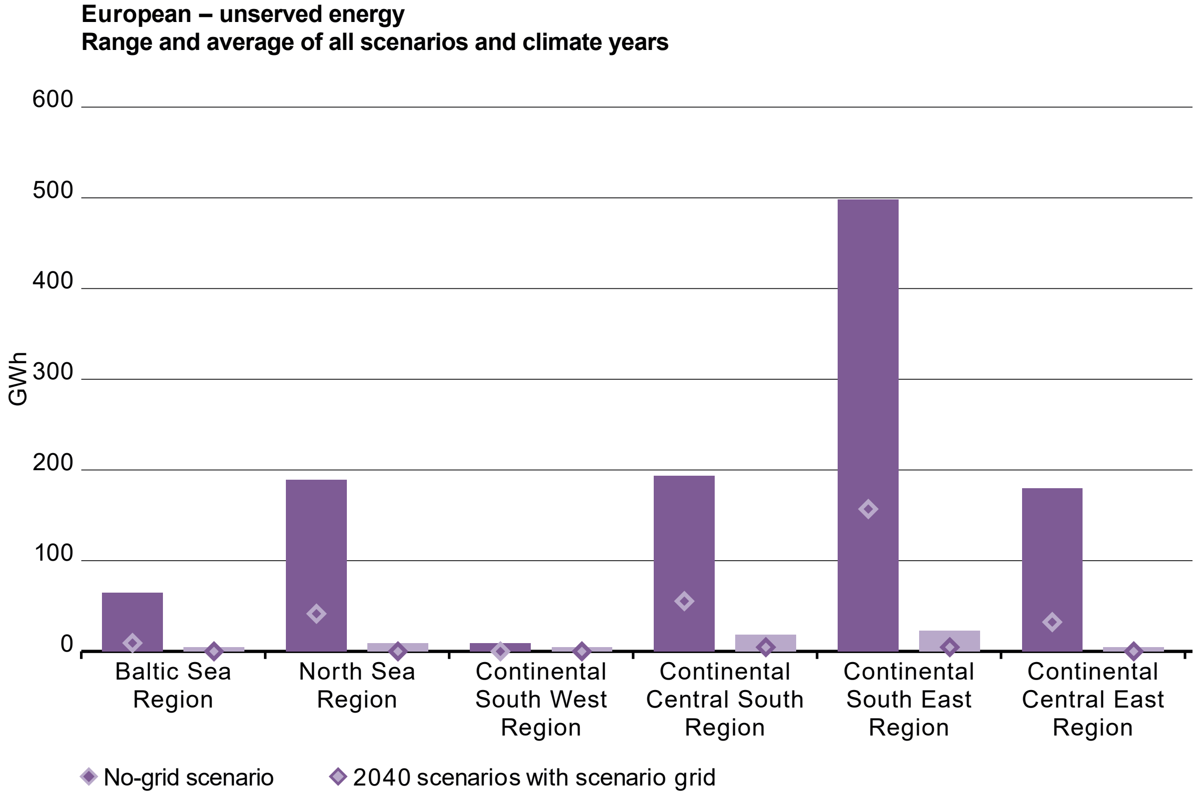
Methodology: unserved energy
Unserved energy means the amount of endcustomer demand that cannot be supplied within a region due to a deficiency in generation or interconnector capacity. In other words, this means the forced disconnection of demand customers, commonly referred to as 'load shedding'.

This security of supply indicator is shown per region in the figures below. The additional cross-border exchange capacities identified lead to a much higher level of security of supply demonstrated by nearly no unserved energy in 2040, that is nearly-zero-load shedding.

The results of the no-grid scenarios confirm that without the ability to rely on cross-border exchanges, many European countries will simply lack generation capacity.

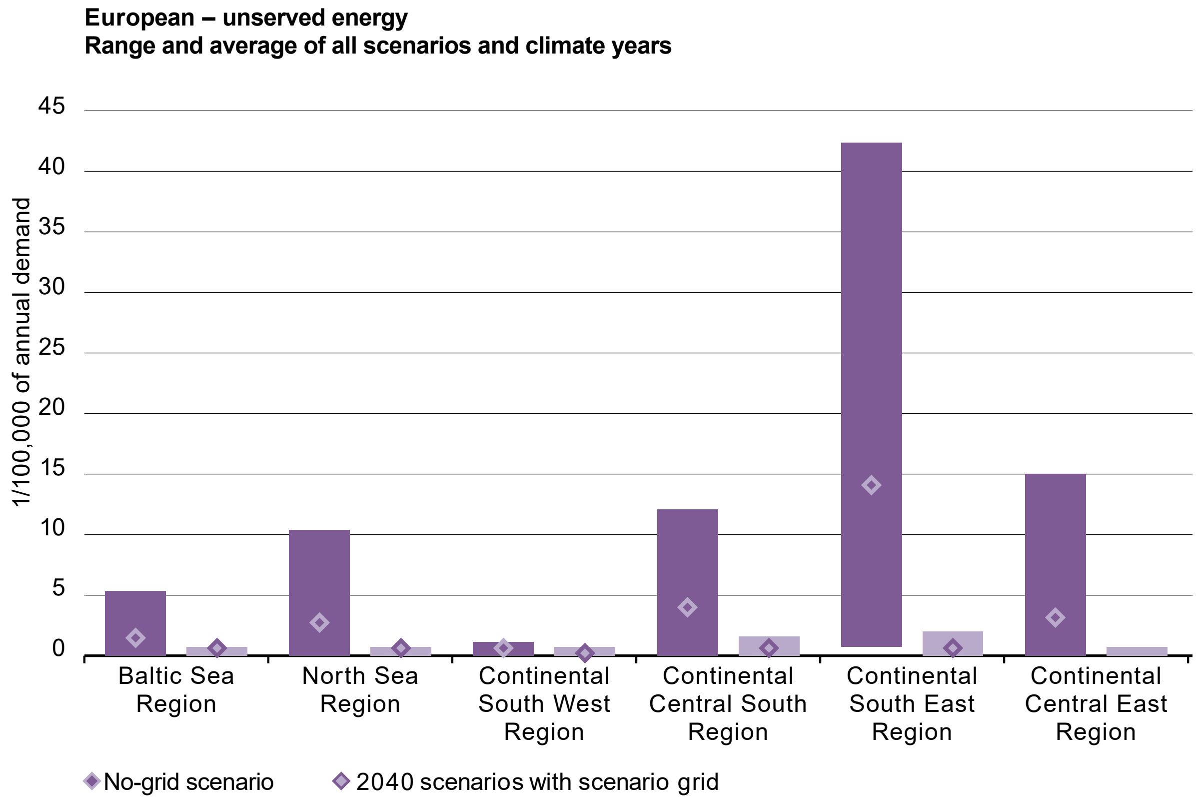
In the no-grid scenario, unserved energy is rising across all regions. These results demonstrate the principle that interconnectors contribute to ensuring adequacy through the sharing of resources in Europe and that they are the basis of a secure and reliable power system in the mid/long-term scenarios.

Figure 11: Unserved energy in 2040, depending on assumed grid status (absolute values in GWh)



To explain the absolute values shown in Figure 11, the figure below shows the amount of unserved energy as a percentage of annual demand.

Figure 12: Unserved energy in 2040, depending on assumed grid status (in percentage of demand)



4.3

Falling short of European climate objectives

No grid is incompatible with the achievements of European emission targets.

In the no-grid scenarios, significant amounts of renewable energy would go to waste as they could not be exported because of the lack of cross-border capacity. In addition, the limitations in cross-border exchanges would be compensated for by local production from peaking units, representing by more CO_2 emissions. Even with the delivery of the infrastructure needed by 2040, the amount of curtailed energy remains very significant despite the increase in interconnection capacities: this confirms that further reduction of curtailed energy will necessitate further optimisation of the geographical spread of RES and/or complementary solutions (storage, etc.) to network development.

It can be argued that in the no-grid case, because RES promoters will know that they will not be able to sell their production in foreign markets and therefore will be unable to benefit from this revenue, they will not build the RES units in the first place. This would reduce the amount of lost or 'dumped' energy from RES, but overall would push up the level of CO_2 emissions.

The light mauve bars show the range of curtailed energy in the three scenarios per region using the capacities as they will be in 2020. The dark mauve bars then show the same regions but provide the range of the curtailed energy using the capacities in 2040.

It is important to keep in mind that all scenarios were developed under the assumption that the CO_2 emissions will be reduced as defined in the European climate goals. That means that on a European level, installed coal capacity and production have been reduced in the 2030 scenarios and even more so in 2040 compared to 2020 and 2025. Any old coal unit that is retired after 2030 will not be rebuilt, i.e. they are not included in the 2040 scenarios if they reach the end of their lifetime.

>156TWh per year

of renewable energy wasted on average because of no grid, which is equal to the total annual consumption of Benelux in 2040. In some situations, up to four times this amount would go to waste.

Beside the CO_2 reductions achieved by the scenarios' transition to a more renewable production system and the increased utilisation of flexible demand, the cross-border capacity increases identified reduce the CO_2 emissions even more. Figure 14 shows CO_2 emissions in 2040, depending on assumed grid status. On average, the grid built between 2020 and 2040 allows for a further 10% decrease in power sector CO_2 emissions as compared to the 1990 levels.

Figure 13: Curtailed energy in 2040, depending on assumed grid status

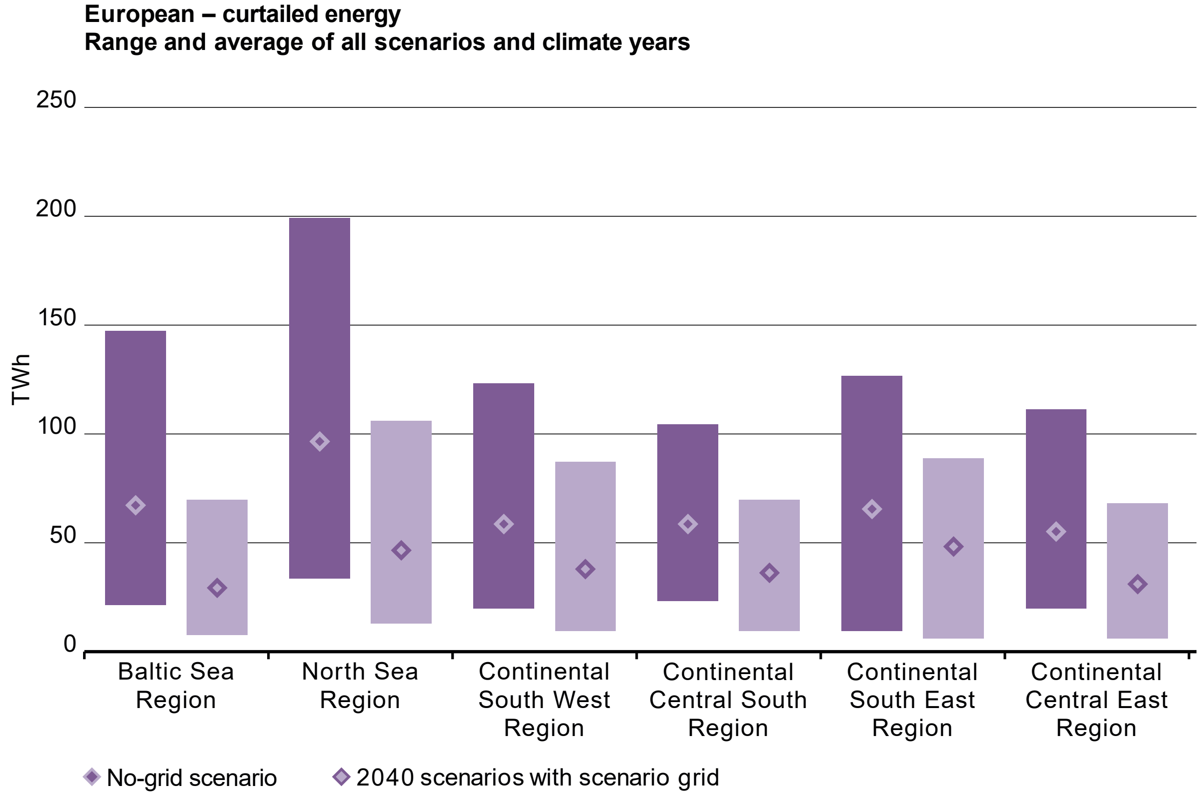
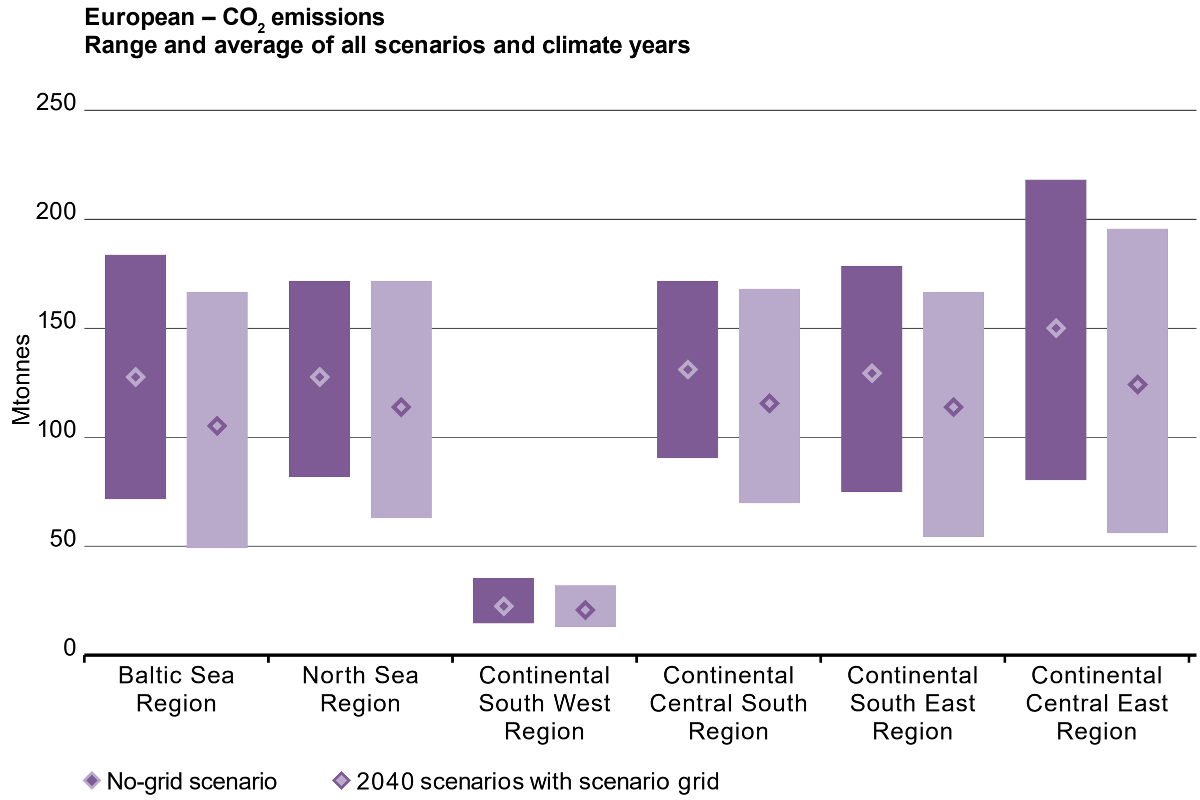


Figure 14: CO_2 emissions in 2040, depending on assumed grid status



4.4

Cross-border and internal physical bottlenecks

Eventually, a low-emitting, integrated, efficient energy market comes down to the networks' ability to handle the physical flows of elect.

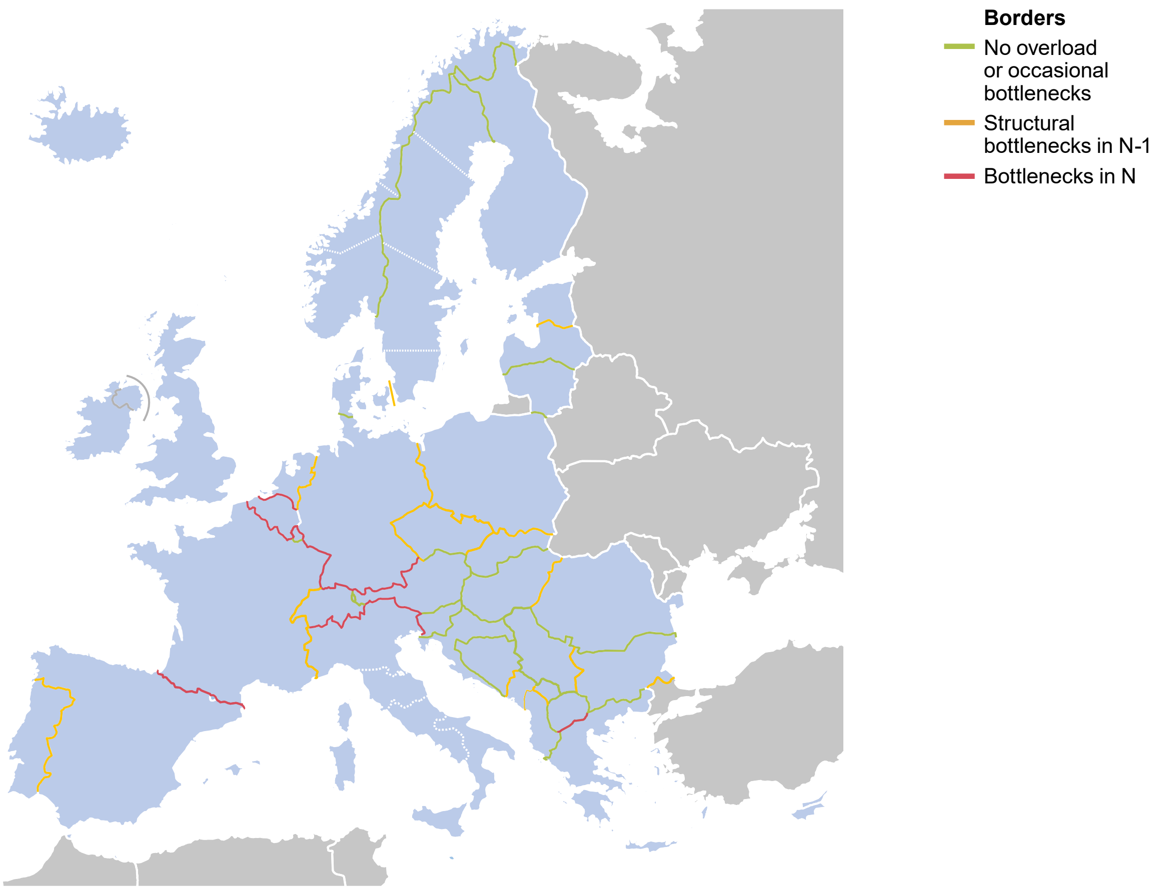
Network studies were conducted to see how far crossborder ties and internal TSO networks are able to accommodate the energy transition by 2040 in the scenarios at stake.

The result of the no grid beyond 2020 scenarios analysis grids can be analysed as follows:

1. Cross-border exchange capacities resulting from TYNDP 2016 would seem to be generally insufficient to enable optimal cross-border exchanges resulting from an economical operation of the European generation mix.
2. At the same time, even in the absence of an increase in cross-border capacity, the internal networks need reinforcements to accommodate the flows resulting from the new generation mixes described in the scenarios.
3. Finally, after increasing cross-border capacity to release limitations mentioned in 1), additional internal reinforcements on top of those ones described in 2) may be required.

Figure 15 shows cross-border AC connections that are overloaded in the 2040 scenarios. Severe bottlenecks (N constraints) appear on borders highlighted in red, while less severe bottlenecks (N-1 bottlenecks) appear on borders highlighted in amber. Both types of constraints are, however, very likely to be solved by network reinforcements enabling an increase in cross-border exchange capacity for the border under consideration.

Figure 15: Future challenges in 2040 scenarios (study based on 2020 grid)



Section 5

New needs in a new set-up: dynamic study results

Beyond the necessity to efficiently ensure a balance between production and demand at any time, the future system must also 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.

Transmission systems in Europe are increasing in complexity. Conventional generation is being displaced by new generation technologies that have different performance capabilities; generation is moving from the higher voltage levels to the distribution networks; and there is a greater level of interconnection between different synchronous areas.

This increases both the interdependency of TSO processes to operate the system in a secure and efficient manner, and the need to take into account the challenges associated with the operation of the future system when designing the transmission network.

These needs are highly dependent on the final portfolio, individual characteristics and technology of the projects that address the capacity needs identified in this report. By presenting a vision of the situation created by the future energy landscape, this report represents a first step towards a reliable and accurate definition of these needs.

Future studies will be necessary to clearly understand the scale and nature of measures to be taken by system operators in order to adapt to the situation presented in this report.

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 to address the specific dynamic stability needs.

Methodology: dynamic stability analysis
This section looks into the way the system would physically respond to the ENTSOs' 2040 conditions. The results it presents are based on an analysis of the hourly demand and generation profiles, testing operational parameters such as inertia and shortcircuit current levels, 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 sections, as well as more detailed results and further analysis are presented in the Technical Appendix.

5.1

Frequency management: system inertia and local frequency variations

Frequency variations occur in power systems due to mismatches between the active power being generated and the power being used by the demand it is supplying.

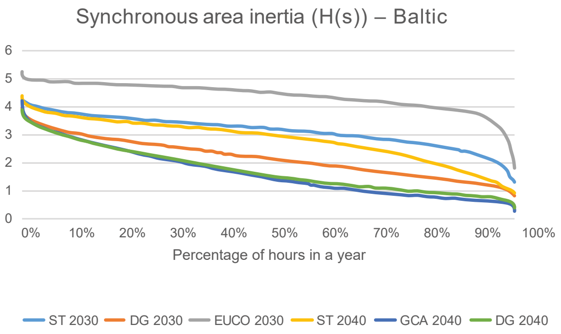
Once a mismatch takes place, the energy stored in the rotating masses of the synchronous generating units, by virtue of their inertia, is released instantaneously balancing of any mismatch (between the raw energy supplied to generating units and the total system demand including losses). The immediate inertial action results in a change in rotor speed and, consequently, system frequency.

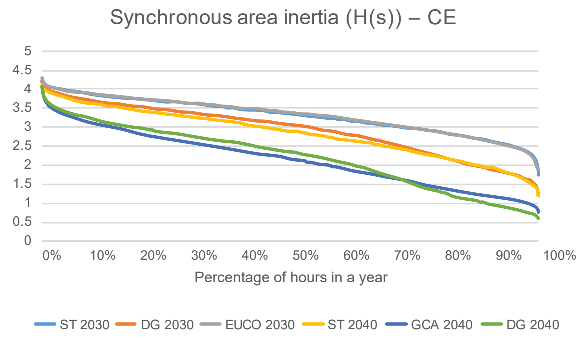
Although this does not solve the power mismatch problem in a sustainable manner, it is essential for instantaneously balancing this mismatch until the balance between generation and demand can be restored.

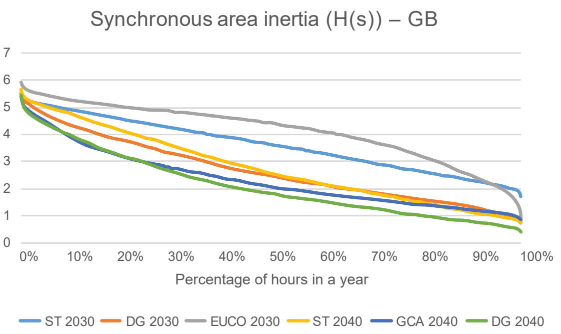
Consequently, the level of inertia provides a useful assessment of the emerging challenges to system operability.

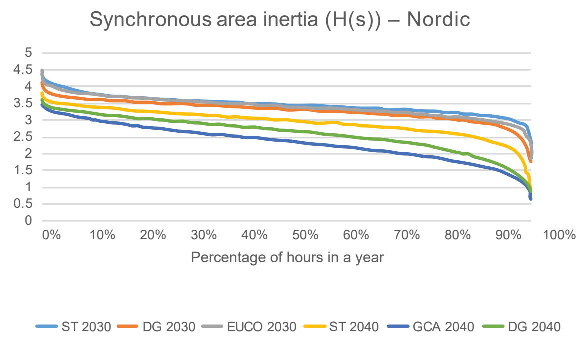
The following duration curves present the percentage of hours in a full year where, for all synchronous areas, the intrinsic inertia from generators is above a given value. The estimated synchronous area equivalent inertia, expressed as H(s), is calculated on the basis of online generators' capacity. 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.

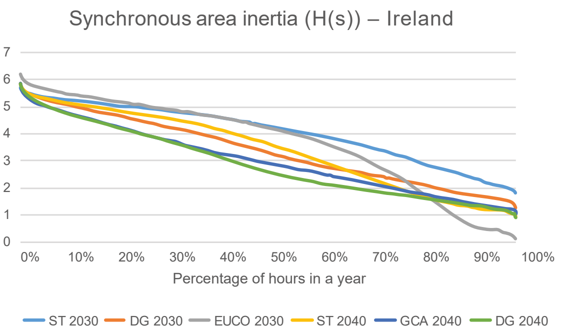
Figure 16: Duration curves of estimated synchronous areas equivalent inertia (H(s))











System inertia trends

The graphs illustrate the reduction in all synchronous areas as we move from the situations in 2030 to the 2040 visions with a higher integration of RES and more distributed generation.

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

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 generationdemand imbalances is important to quantify. If the frequency changes too 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 not see the same size of frequency excursions (unless a significant disturbance occurred, such as a system split event).

Focus: the case of Ireland indicates the new levels of inertia will create new needs
Ireland, as the smallest and a weakly interconnected system, with high levels of instantaneous levels of intermittent renewable power, has already identified the inertia limits that it may accept on the network.

The operational limit up until 14th November has been set at 20,000MWs* (MW seconds) for system operation with up to 65% SNSP (system non-synchronous penetration). SNSP is mainly defined by the level of non-synchronous renewable generation but is impacted by import and export power into the All Ireland synchronous network (Ireland and Northern Ireland). These operational limits are contingent on the rate of change of frequency that the equipment on the system can withstand. Currently, this is 0.5Hz per second, but it is planned to raise this to 1.0Hz per second which will result in a reduction in the required inertia to around 12,000MWs. At the moment, the combination of all machines in operation must always provide this inertia, meaning that the resulting inertia constant for the system (H) defined as the MWs divided by the combined rating of the machines in MVA will vary with the number of machines in operation to meet demand. As can be seen in Figure 16 above, which shows system inertia trends, Ireland is predicted to have significantly reducing inherent system inertia in later years as we move towards high levels of non-synchronous generation. This means that mitigation measures will be required to manage this situation.

EirGrid has been working with the regulators in Ireland to implement a change to the market structure to increase significantly the payments for ancillary services, including inertia products, to mitigate this issue. It is expected that these changes will incentivise the market to deliver new ancillary service providers (in the event that this does not occur, EirGrid will bring forward projects directly). It is intended to recalculate and rebalance these payments annually to ensure the market continues to deliver as the system evolves.

* More recently, as part of a trial on increasing the SNSP, limit inertia was increased to 23,000MWs during the trial. However, it is expected to be reduced to 20,000MWs once the trial is completed.

The analysis of inertia by country also brings further insight regarding the level of complexity in a system split event. A system split is more prone to occur across congested transit corridors, thereby interrupting these transits. As the 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 low frequency demand disconnection (LFDD) or fast frequency response. Defence plans[6] are designed to help during severe disturbances, but cannot stabilise all system split scenarios with extreme imbalances.

Different solutions and mitigation measures contribute to securing the power-system performance in case of disturbances related to frequency. These services are more difficult to obtain from variable renewables, and significant effort will probably be required to develop the existing capacities, in particular by implementing the network codes, and bringing new technologies into the system (such as fly-wheel inertia storage).

Unlike conventional generation with costly but controllable sources of primary energy, RES utilise primary energy sources that are free but variable in nature. Hence, the high installed capacity of RES and their close-to-zero marginal costs cause conventional generation, with primary energy sources independent of weather conditions, 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, in order to maintain the frequency equilibrium. To cope with this situation, new flexibility sources will be necessary both from the generation and demand-side response. This includes new roles for thermal plants, RES participation, demand side response, and storage. Also from the network side, strong interconnection between countries will be essential to exchange the power flows from flexibility sources.

ENTSO-E will further analyse to what extent the existing solutions will need to be extended to guarantee a secure electricity system. The analyses above represent a positive first step to enable the changes needed to provide adequate dynamic behaviour.

[6] 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 disturbance and blackout state.

5.2

Transient and voltage-stability-related aspects

Short-circuit power has commonly been used as an indicator of the system strength and, consequently, the ability of a synchronous generating unit to stay 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 decline. Also, a generator's contribution to providing a short-circuit reduces the further away it is so, as the generated power has to be transmitted over 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 in the system also monitor and try to respond to correct any excess or shortfall accordingly. Fluctuations can 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, 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 from the embedded generation.

The large fluctuations in reactive power demand and reactive losses, and the reduction in shortcircuit 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 in 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. Consequently, it is necessary to ensure that sufficient alternative measures are made available to ensure that voltage excursions can be managed within permissible limits.

The exact location and technology of projects to address the assessed needs for increased capacity in 2040 are not known at this time. These will be highly influential on future changes in system strength and reactive power provision compared to those at present.

Consequently, the corresponding projects which will compensate for these changes and provide adequate dynamic behaviour cannot currently be determined either. However, ENTSO-E is committed to and will conduct further studies to assess the mitigating needs and projects for the 2040 scenarios as capacity-related projects are developed.

5.3

How to adapt? Possible solutions for future system operations

The situation described above, along with details in the Appendix of this document will lead to new needs, the exact nature and scale of which will need to be assessed in detail by system operators. This is 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:

- Implementation of connection codes: they will be essential to ensure that the necessary technical requirements from generators, HVDC and demand related to dynamic stability are implemented;
- At the moment, immediate inertial response can only be met by synchronous generators. After immediate inertial response, fast-frequency response by sources other than synchronous generation are needed: converter-connected generation, demand-side response, storage (including batteries), and reserves shared between synchronous areas using HVDC;
- In the future, new capabilities, not yet available, such as grid-forming converters[7], are currently promising to be capable of providing immediate inertial response. Grid-forming converters will need research and development to demonstrate they could be a solution and can be incorporated into the grid in the future[8];
- 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, which 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 a 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 Distribution System Operators;
- 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: synchronous condensers, SVCs, STATCOM, HVDC, series compensation, etc. to maintain stability and avoid curtailment of RES generation;
- Observability and controllability of distributed resources by the TSOs and DSOs as well as strong coordination between both operators.

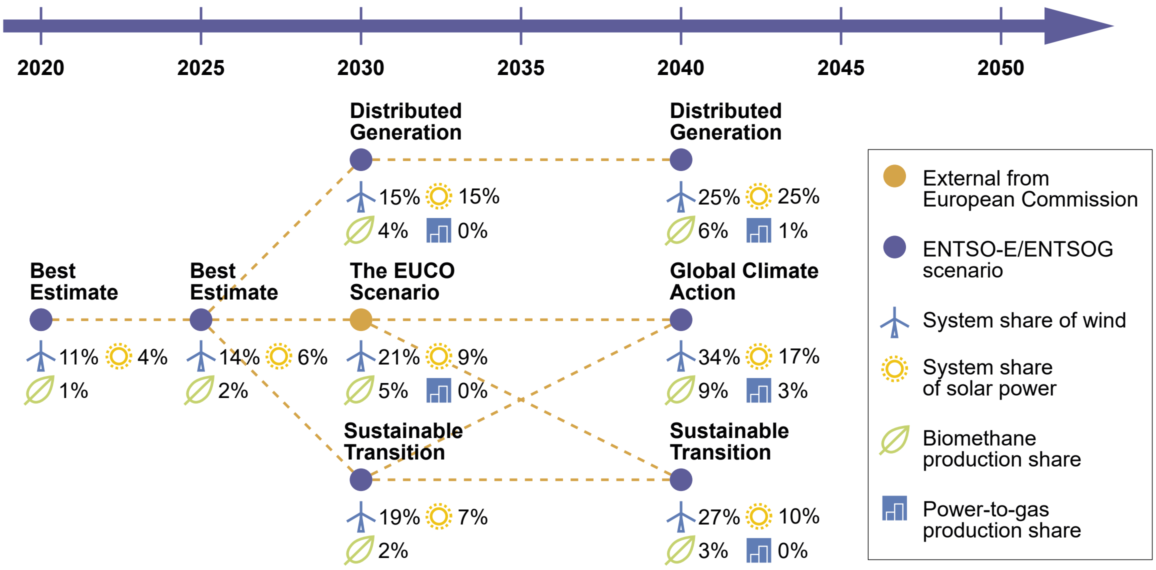
[7] Implementation Guiding Document – High Penetration of Power Electronic Interfaced Power Sources: https://www.entsoe.eu/Documents/Network%20codes%20documents/Implementation/CNC/170322_IGD25_HPoPEIPS.pdf
[8] An example of related investigations is the MIGRATE project – Massive InteGRATion of power Electronic devices: https://www.h2020-migrate.eu/

Section 6

Description of the scenarios

Figure 17 overleaf gives an overview of the 2018 ENTSOs' scenarios which served as a framework to identify the needs presented in this document.

Figure 17: Scenario-building framework indicating bottom-up and top-down scenarios



The present study analysed the three 2040 scenarios:

Distributed Generation (DG)

Presumers at the centre – small-scale decentralised generation, batteries and fuel switching. Society engaged and empowered by strong EU policies and efficient Emissions Trading System. High economic growth. High electrification of heating and transport sectors. An efficient usage of renewable energy resources is enabled at the EU level as a whole.

2030 and 2050 EU emission targets are reached.

Global Climate Action

Full-speed global decarbonisation, large-scale renewables development in both electricity and gas sectors. High penetration rate of disruptive technologies (smart cities, demand response, power to gas etc.).

Global methods regarding CO_2 reductions are in place and the EU is on track for its 2030 and 2050 decarbonisation targets. An efficient usage of renewable energy sources will be secured by a strong EU policy.

Sustainable Transition

Targets reached through national regulation, emission trading schemes and subsidies. Steady RES growth, moderate economic growth, moderate development of electrification of heating and transport. Scenario in line with the EU 2030 target but slightly behind its 2050 target.

The regulation, with more national focus on climate change, takes the shape of legislation that imposes binding emissions targets. The ST scenario is driven by national subsidies and will result in an inefficient usage of renewable resources.

A more detailed description of the scenarios is available in the 'Scenario Report': https://www.entsoe.eu/Documents/TYNDP%20documents/14475_ENTSO_ScenarioReport_Main.pdf Key figures.

Figure 18: Electricity installed generation capacity by source and scenario

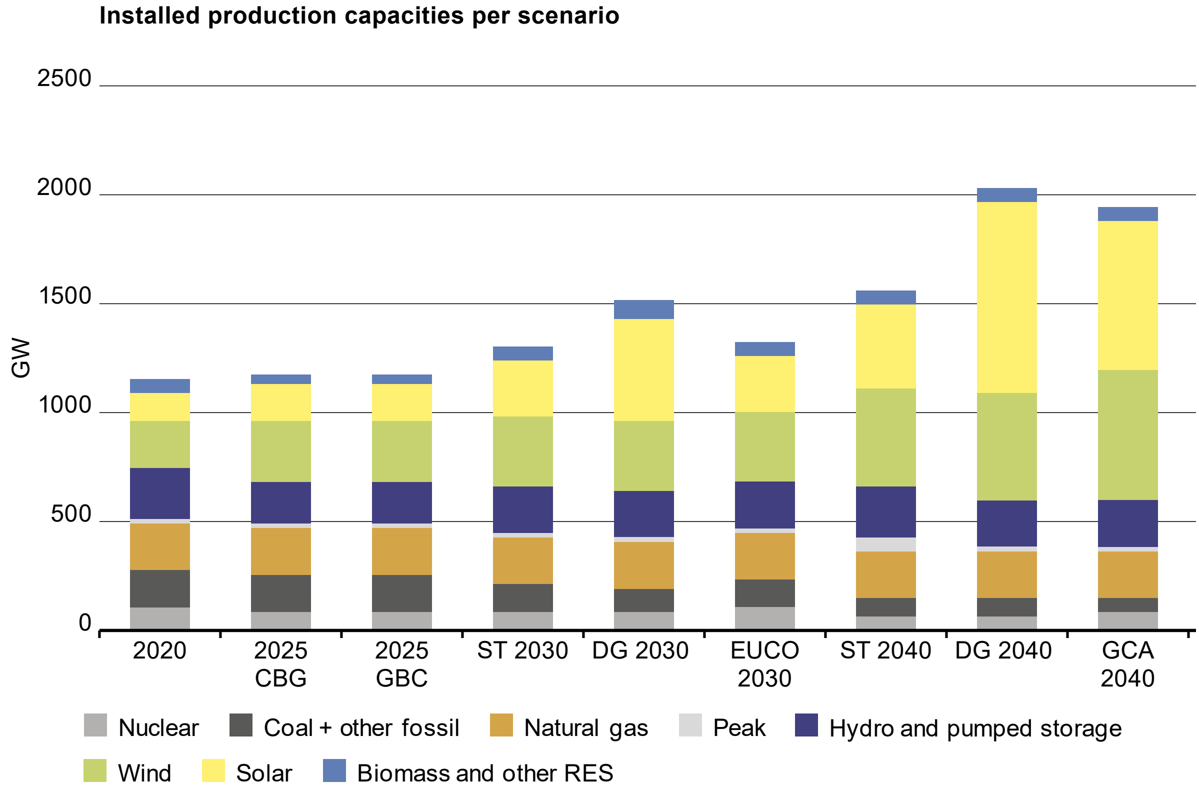


Figure 19: Electricity net generation by source and consumption per scenario

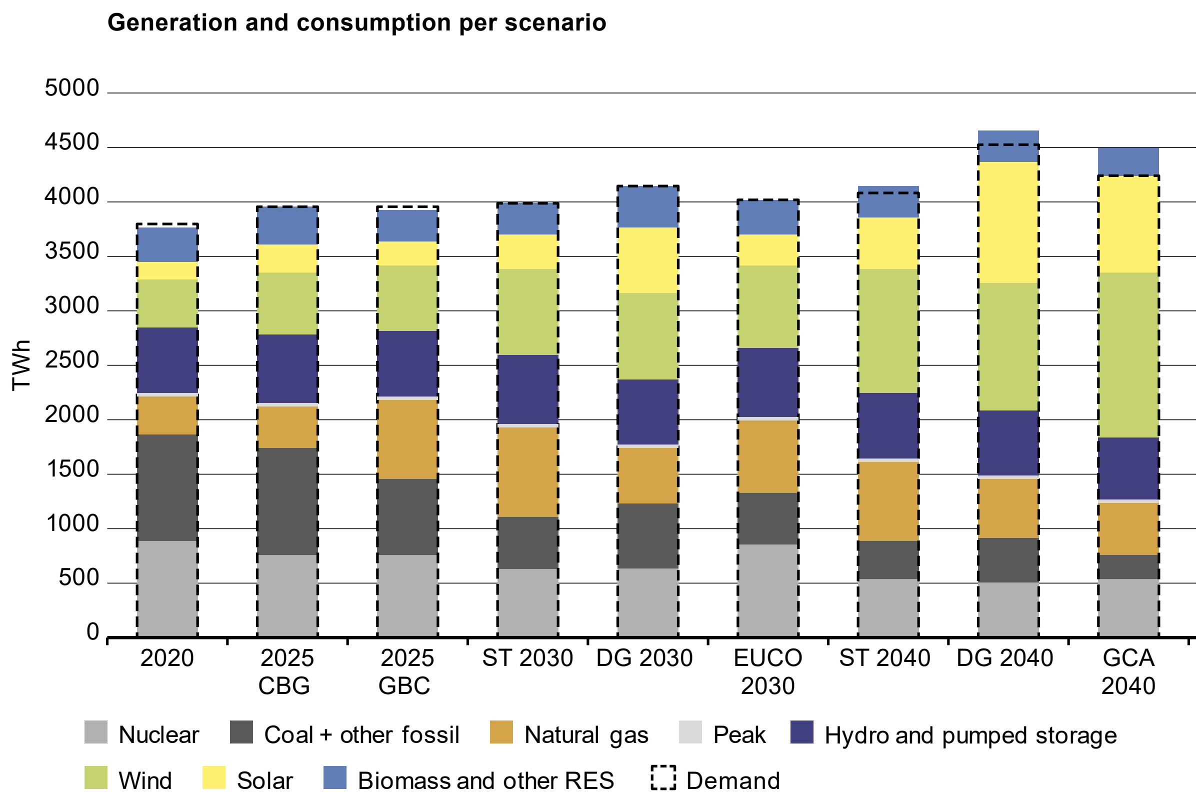
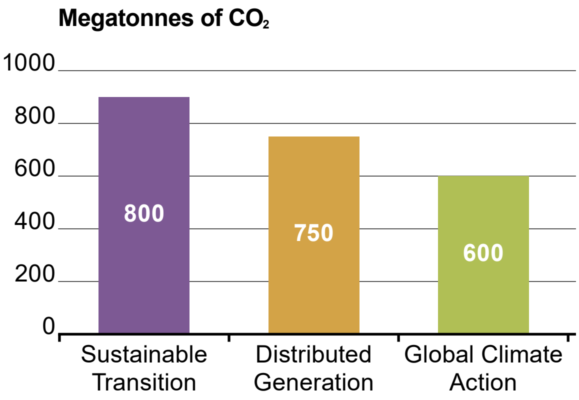
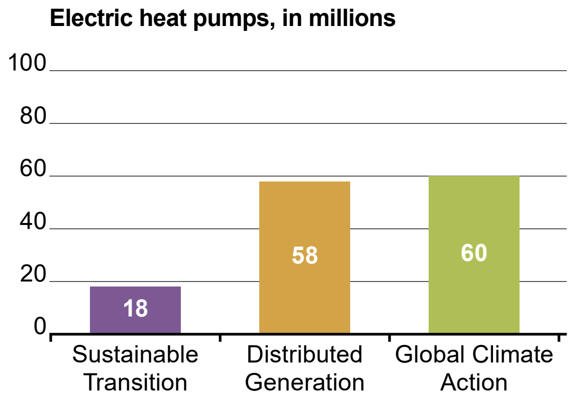
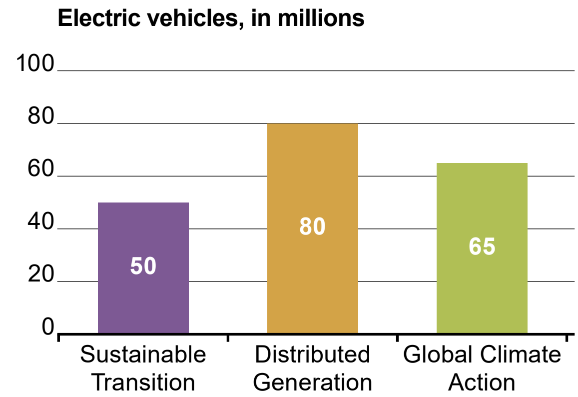
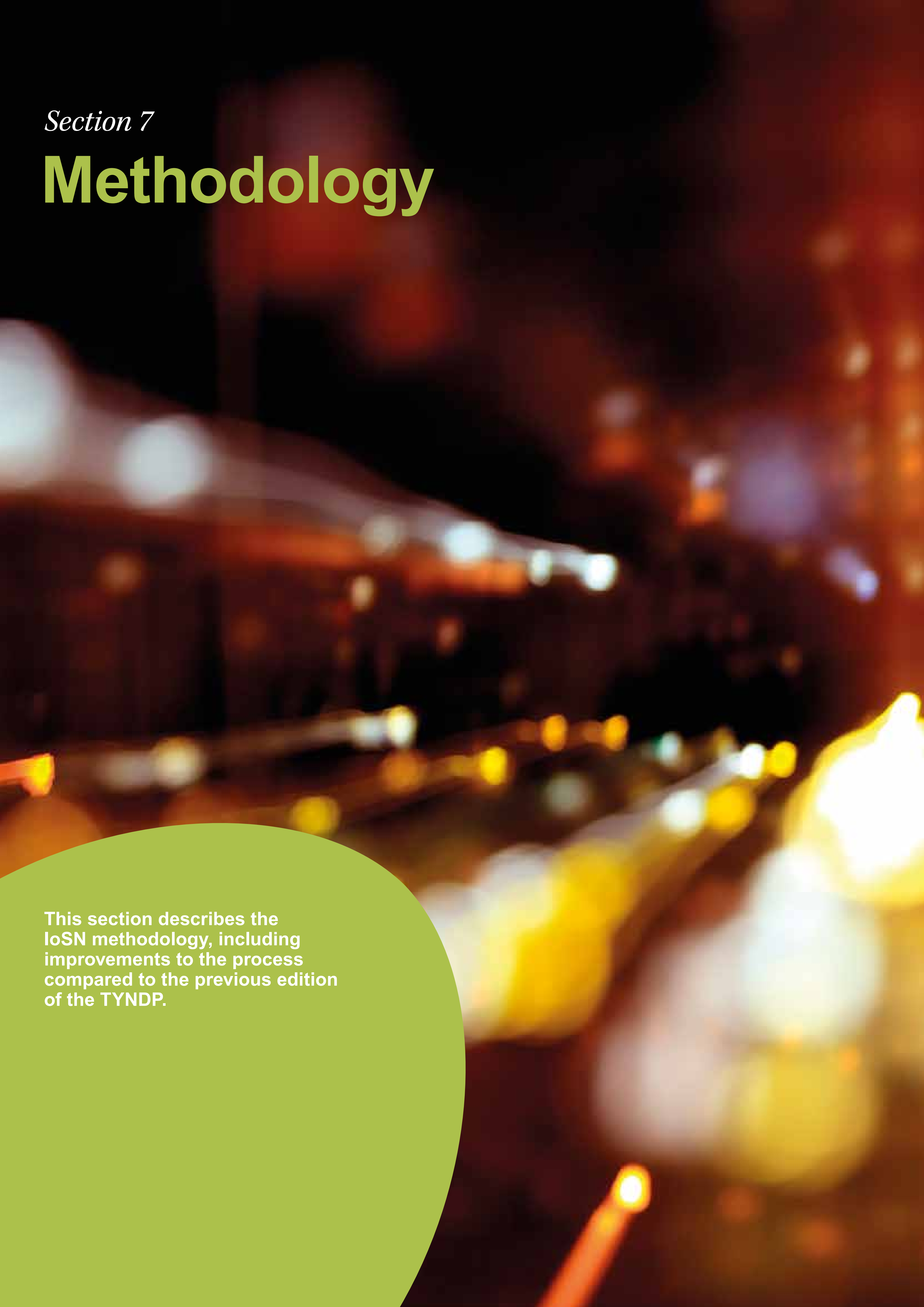


Figure 20: 2040 key figures









Section 7

Methodology

This section describes the IoSN methodology, including improvements to the process compared to the previous edition of the TYNDP.

Details about the methodology have been divided into two subsections, describing the market as well as the network studies approaches:

— The market studies methodology is described in section 7.1. It describes the simulations carried out by market models to identify future needs based on SEW and standard costs of potential capacity increases. It also includes the identification process of additional increases due to integration of RES and avoidance of SoS issues.
— The network studies methodology is shown in section 7.2. It covers a standard costs evaluation, load-flow analyses and a description of security analyses.

The main improvements regarding the modelling and the methodology itself, when compared to the previous TYNDP 2016 package, comprise:

— NEW! Focus on long-term 2040 scenarios for the IoSN for the first time.

— NEW! Several climate conditions (wind, solar, hydro) have been included in the analyses.

— NEW! IoSN, considering not only economic indicators but also including SoS and RES integration.

— NEW! Medium- and long-term scenarios have been developed in close cooperation with ENTSOG and with external stakeholder involvement.

— Improved! More consistent approach to determine demand profiles for each zone.

— Improved! Demand-side response as well as electric vehicles have been considered with a more refined approach that improves the accuracy of the calculations.

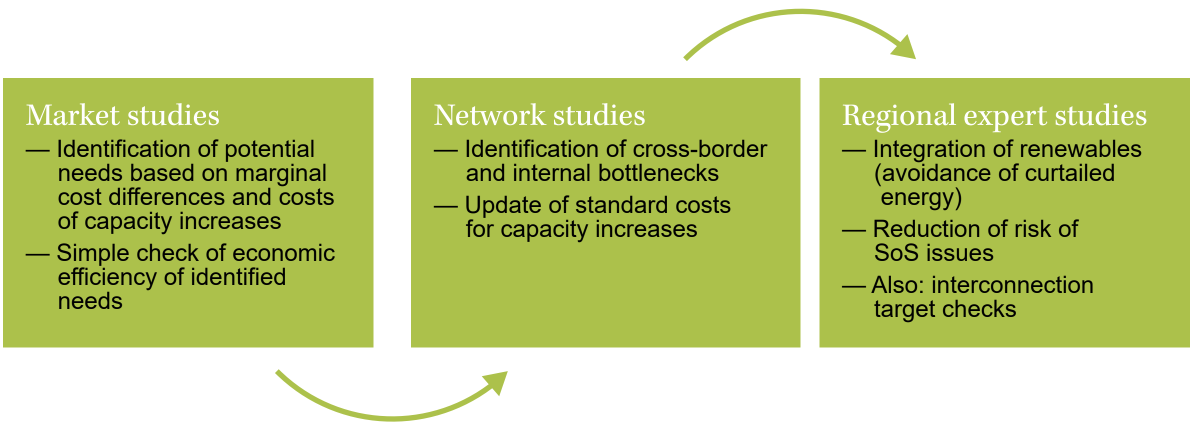
In parallel with the IoSN process, dedicated market and network studies have been carried out to show what would happen in the 2040 scenarios if the grid did not evolve beyond 2020. These studies highlight the main problems, system needs and present drivers for the continued development of the transmission system.

As a result of these studies, the following main indicators are provided:

— Unserved energy [GWh]
— Curtailed energy [GWh]
— CO_2 emissions [Mtonnes]
— Average hourly cost differences [€] and marginal cost yearly average [€]
— Cross-border and country-internal bottleneck maps.

The figure below shows the main process of identifying capacity increases:

Figure 21: Overview, IoSN approach



7.1

IoSN methodology – market approach

The market simulations, performed within the IoSN framework, have been carried out for all the TYNDP 2018 long-term 2040 scenarios Sustainable Transition, Global Climate Action and Distributed Generation.

Three different climate years (1982, 1984 and 2007) have been considered for each scenario. In order to provide high-quality and consistent results, three different market tools (PowrSym, BID and Antares) have been used. The Technical Appendix section 1.6 provides a description of the methodology used to determine which climate years to use.

The aim of these studies was to identify potential capacity increases in a coordinated pan-European manner, also building on the expertise of all TSOs. Potential capacity increases could be triggered by drivers like market integration, integration of renewable energy sources and SoS issues.

The studies started using a 2030 grid[9] and considered an iterative approach carried out individually for every scenario. Market models were used to calculate hourly marginal cost differences between countries. For the borders with the highest factor of marginal cost difference divided by the standard cost of an increase, an NTC increment was studied. The SEW from this increase was compared to the investment cost of a potential standard project on that border and, if the calculation gave a positive result, the increase on this border was included in the next round of simulations.

The more reinforcements were added on a given border, the lower the SEW from additional increases was and generally the more expensive additional projects became. Thus, the proper capacity was obtained when the expected additional SEW no longer exceeded future investment cost.

It must be noted that this approach included some simplification. For instance, only the SEW increase due to an increased market coupling was taken into account as a main driver, whereas other elements could also be taken into account in a definition of a new specific additional capacity increase. Another simplification was the fact that the screening was carried out with a standard capacity increase of 500MW to harmonise the approach across the areas as much as possible. Finally, the standard costs of the increases were assessed by experts, taking into account, as far as possible, the specificity of the area (e.g. presence of mountain or sea), internal grid considerations as well as knowledge from previous projects at these borders (if any).

In addition to market integration, SoS and RES integration were considered in the IoSN process. Market analyses provided results of simulations where the capacity increases identified in the SEW iterations were implemented. Regional market and network experts considered the output of these simulations in their investigation of additional capacity increases based on SoS and RES needs. The main parameters considered by the regional experts were:

— For security of supply needs10, the remaining capacity, defined as

$$RC(\%) = \frac{\text{Avail. capacity}(h) - \text{Demand}(h) \pm \text{IC contribution}(h)}{\text{Demand}(h)}$$

— For RES integration needs, the curtailed energy (GWh) (provided directly by the tools used in the process) was considered.

Finally, with the scenario capacities derived from the steps above, market analyses investigated if the 15% interconnection ratio criteria (15% of RES installed capacity) were met in all market nodes. If not, then regional experts could provide additional capacity increases.

It is worth pointing out that the additional capacity increases identified in this step refer to potential needs to be further investigated, and they will not necessarily result in new projects in TYNDP 2018.

[9] TYNDP 2016 V1 grid, used to speed up the computation (TYNDP 2018 values were still being defined in mid-2017).

[10] Since TYNDP 2018 scenarios are adequate by definition, it is not possible to see any energy not supplied. This definition will be discussed during the TYNDP 2020 scenario-building consultation phase.

7.2

IoSN methodology – network approach

Based on the results of the market simulations, network studies were performed on detailed grid models which included all buses, lines and transformers in the transmission systems explored. The scope of these network simulations was to analyse if the capacity increases suggested by market studies increased network bottlenecks.

Network analyses have been carried out on an hourly year-round calculation basis but where the translation from market to network studies was done using a combination of:

- PTDF (power transfer distribution factor) matrix approach: market data for each hour was transposed into the simplified grid represented by the PTDF matrix. Then PTDF flows were calculated for each of the 8,760 hours, on each synchronous border and each of the internal transmission lines elected by each TSO;
- Computing all 8,760 hours in a year in DC or AC load flows directly in load-flow tools with a detailed representation of the grid model.

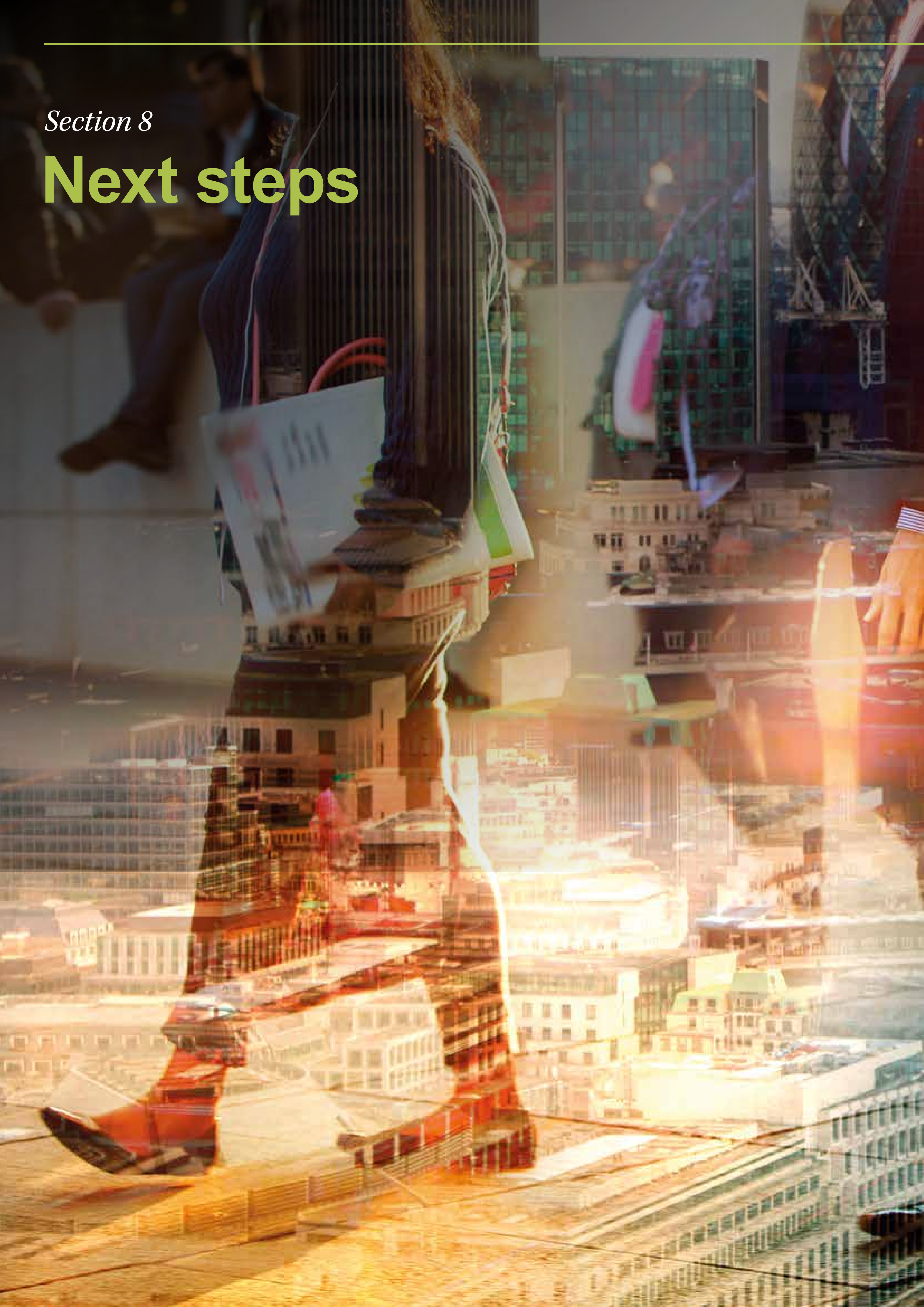
Bottleneck analysis was performed taking into account security of the network, that means fulfilling the planning standards of each system, with all grid elements available (N criterion) and also considering the outage of every relevant grid element (N-1 criterion).

Results of the network analyses were maps showing:

- Cross-border challenges between countries when going to 2040 scenarios but not evolving the grid beyond 2020. These maps show if borders are safe (green), if bottlenecks are identified in N-1 situations (yellow) or if bottlenecks are already present in N situation (red);
- Internal challenges inside countries when the production/consumption of the 2040 scenarios is applied to the internal grids of 2020. Countries were coloured green if only some reinforcements are needed, yellow if an important number of reinforcements are needed or red if a huge number or heavy reinforcements are needed (red);
- Additional internal challenges inside countries due to capacity increases as a result of the market step of the IoSN approach.

Section 8

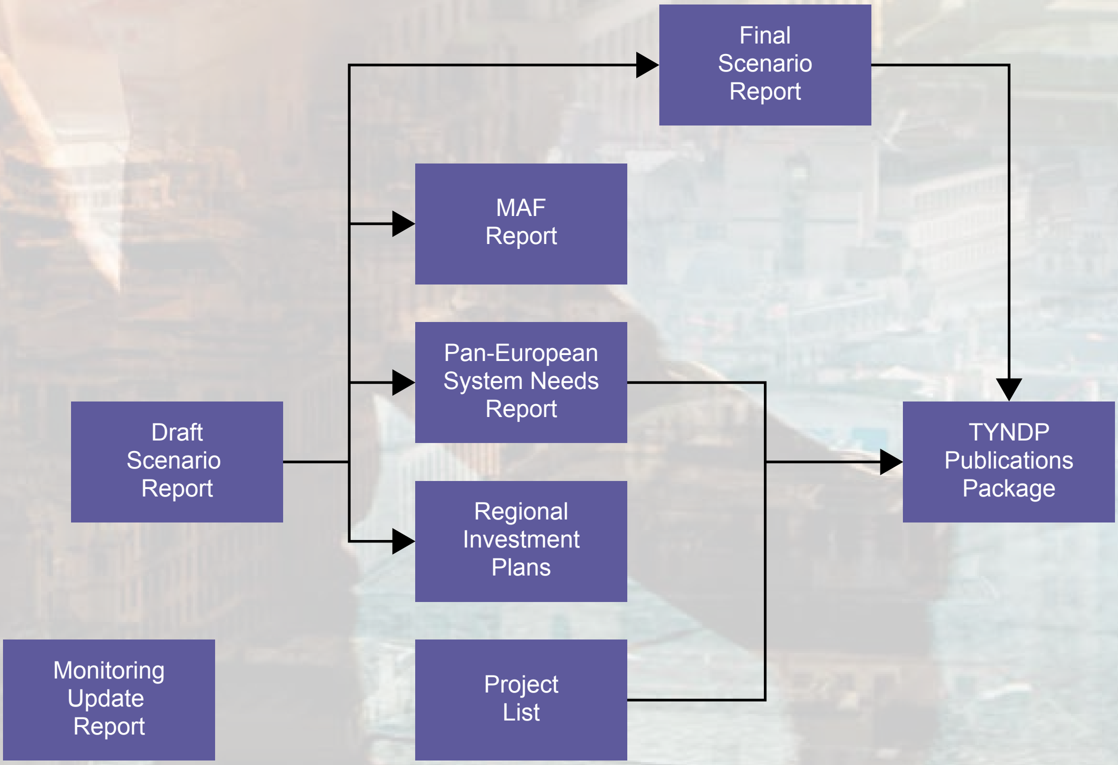
Next steps



This report describes, for the first time, studies focusing on the 2040 time horizon. Many new system needs were identified for this long-term time horizon and it could be concluded that additional capacity increases are necessary to evolve the European energy system in order for it to be on track to fulfil the climate goals for 2050.

ENTSO-E is now working on solutions for the identified needs. In summer 2018, the first draft of the TYNDP 2018 document package was published for consultation. This package, alongside a number of specific Insight Reports, included CBAs of all approved projects submitted to ENTSO-E for assessment. It allows all stakeholders to understand how a project contributes to overcome the energy trilemma, i.e. a sustainable, affordable and secure European energy system. After the public consultation phase at the end of 2018, the TYNDP was submitted to ACER for opinion and published in its final version in October 2019.

Figure 22 below gives an overview of the publications in the TYNDP 2018. This pan-European System Needs report is published together with the six Regional Investment Plans and Summary leaflets of these documents.



Section 9

Appendices

9.1

Abbreviations

The following list shows abbreviations used in the current report:

Acronym	Description
AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
CBA	Cost-Benefit Analysis
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power Generation
DC	Direct Current
EH2050	e-Highway2050
EIP	Energy Infrastructure Package
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSOG	European Network of Transmission System Operators for Gas
EU	European Union
GTC	Grid Transfer Capability
HV	High Voltage
HVAC	High Voltage AC
HVDC	High Voltage DC
IEA	International Energy Agency
IEM	Internal Energy Market
KPI	Key Performance Indicator
LCC	Line Commutated Converter
LOLE	Loss of Load Expectation
MAF	Mid-term Adequacy Forecast
MS	Member State
MWh	Megawatt Hour
NGC	Net Generation Capacity
NRA	National Regulatory Authority
NREAP	National Renewable Energy Action Plan
NTC	Net Transfer Capacity
OHL	Overhead Line
PCI	Projects of Common Interest
PINT	Put IN one at the Time
PST	Phase Shifting Transformer
RegIP	Regional Investment Plan
RES	Renewable Energy Sources
RG BS	Regional Group Baltic Sea
RG CCE	Regional Group Continental Central East
RG CCS	Regional Group Continental Central South
RG CSE	Regional Group Continental South East
RG CSW	Regional Group Continental South West
RG NS	Regional Group North Sea
SEW	Socio-Economic Welfare
SoS	Security of Supply
TEN-E	Trans-European Energy Networks
TOOT	Take Out One at the Time
TSO	Transmission System Operator
TWh	Terawatt Hour
TYNDP	Ten-Year Network Development Plan
VOLL	Value of Lost Load
VSC	Voltage Source Converter

9.2

Terminology

The following list describes a number of terms used in this System Needs Analysis report.

Term	Description
Cluster	Several investment items, matching the CBA clustering rules. Essentially, a project clusters all investment items that have to be realised in total to achieve a desired effect.
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.
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.
Corridors	The CBA clustering rules proved challenging for complex grid reinforcement strategies: the largest investment needs may require some 30 investment items, scheduled over more than five years but addressing the same concern. In this case, for the sake of transparency, they are formally presented in a series – a corridor – of smaller projects, each matching the clustering rules.
Cost-benefit analysis (CBA)	Analysis carried out to define to what extent a project is worthwhile from a social perspective.
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.
Investment	Individual equipment or facility, such as a transmission line, a cable or a substation.
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.
Project	Either a single investment or a set of investments, clustered together to form a project, in order to achieve a common goal.
Project candidate	Investment(s) considered for inclusion in the TYNDP.
Project of common interest	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 network	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 gas demand and gas supply, gas infrastructures, fuel prices and global context occur.
Take Out One at the Time (TOOT)	Methodology that consists of excluding investment items (line, substation, PST or other transmission network device) or complete projects from the forecasted network structure on a one-by-one basis and to evaluate the load flows over the lines with and without the examined network reinforcement.
Ten-Year Network Development Plan	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.
Total transfer capacity (TTC)	See Transmission capacity below.
Transmission capacity (also called total transfer capacity)	The maximum transmission of active power in accordance with the system security criteria which is permitted in transmission cross-sections between the subsystems/areas or individual installations.
Vision	Plausible future states selected as wide-ranging possible alternatives.

9.3

Useful information

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