e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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WP 2	**Developing the Grid architecture options as a function of the retained scenarios**		

D2.3

System simulations analysis and overlay-grid development – Digest

		Date & Visa
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This document is a digest of deliverable 2.3 “System simulations analysis and overlay-grid development“.

1. Introduction

The European target to drastically reduce the CO2 emissions by 2050 could create new major transmission needs in Europe, their identification is one of the main objectives of the e-highway2050 project. In deliverables D1.2 and D2.1 of the project, five scenarios of generation, demand and storage were defined to encompass a wide range of possibilities to reach the CO2 reduction target in 2050. The task 2.3 described hereafter aims at identifying the required grid architecture for each one of these five scenarios. That is to say the additional transmission corridors (including their target capacities) to be developed on top of a starting grid. These architectures are allocated a cost and a benefit following a methodology explained in depth in the document.

Main assumptions

The accuracy of the results illustrated in this report depends strongly on the used input data and the used methodology. It must be kept in mind that the system simulations and therefore the development of reinforcements follow these basics. Real future developments that deviate from the assumptions made in the scenarios, especially the generation mix, might lead to other propositions of grid reinforcements.

Given the time horizon of this study (2050) and the size of the playfield, a zonal approach (clustering) was chosen in WP2. Consequently the granularity of the results presented here is not as accurate as in a study that would tackle a closer time horizon and use a full grid model (TYNDP for instance, where detailed consistency of projects is given). The clustering approach enables focusing on transmission needs between clusters, only, thus does not reveal needs for intra-cluster reinforcements. Another consequence is that the priority has been set on the detection of major electric energy transportation issue. That is to say long distance and large capacity reinforcements (often greater than 2GW) and does not assess if smaller reinforcements would prove necessary.

The analyses in this task pursue a conservative approach to assess new transmission corridors. Only corridors that are required and beneficial even under difficult circumstances are suggested. The definition of the initial grid transmission capacities (GTC) within the cluster model has been taken from deliverable 2.2. Here an approach focusing on the thermal capacities between clusters was applied. Since this does not give credit to operational issues of the grid, defined GTCs tend to be higher than on could expect in daily grid operation. Therefore the given architectures per scenario present the minimum required grid reinforcements in each scenario – “no regret investments”. Beyond those, further reinforcements can be required and beneficial. The starting grid, assumed in the analysis, builds on a full realization of the TYNDP 2014 projects. Without their realization, the proposed reinforcements would be different.

It should be kept in mind that the generation capacities were defined following a top-down approach that ensures a European consistency; in particular there are no excessive extra generation capacities to secure independent national system adequacy. To realize such objectives, a very strong collaboration between countries is required in some scenarios. This coordinated development may differ from the combination of national development plans or from ENTSO-e’s Ten Years Network Development Plan visions. Only grid solutions have been implemented to solve the identified issues. Other solutions like more storage or more generation were not considered.

The architectures proposed hereafter can be understood as additional capacity requirements that are required beyond the grid expansion plan that has been issued in ENTSO-e’s Ten Years Network Development Plan 2014 (TYNDP ‘14). Some of these projects set already a basis for a future e-Highway system as they are comparable in use, capacity and distance, e.g. the HVDC corridors in Germany and southwest France and from UK to continental Europe.

For the proposed architectures no detail is given into this work package on the timing of their implementation. This will be further analyzed in WP4.

The results provided in this document offer a cross vision of the grid development expectations in 2050 for the five scenarios. This enables the identification of shared solutions between scenarios, and thus this can put into light robust reinforcements that could be refined and derived into real projects in more detailed studies.

2. Methodology

3.1. Goals and main steps

For the purpose of grid development, "system" simulations are performed with Antares[1]. They combine a detailed modelling of generation, demand and grid :

- The **units commitments** and the use of storage are **optimized to minimize the overall cost** of the system. The European system is optimized in one shot and a perfect market is assumed.
- Simulations are **probabilistic :** they are carried out for 99 Monte Carlo years that present the combination of 11 different solar & wind "years" with 3 different demand "years" (temperatures) and 3 different hydrologies (e.g dry, average, wet "years"). Thus this set of 99 MC years captures the variability of the solar, wind and hydro generation, availability of power plants, as well as the level of demand.
- The optimization takes into account **grid characteristics:** equivalent impedances and equivalent physical capacities. As a result, both Kirchhoff's laws are respected.
- The time step resolution is **one hour** and simulation covers a period of **one year.**

Within the study, network constraints effects are measured by the difference between two simulations:

- **"Copperplate" situation** - Case in which transmission grid is assumed to be without constraints i.e. where network capacities are set to infinite
- Simulation with grid constraints : Case in which capacities are limited to
    - the "**starting grid**"[2] at first,
    - the "starting grid" + Transmission Requirements (TR)[3] in the reinforcement process.

The "copperplate" simulation gives the upper limit of what could be achieved by grid reinforcement to ensure system security and optimize operating costs. On the contrary, the "starting grid" simulation gives the lowest level of system security than can be achieved with the 2030 transmission network status after implementation of 2050 demand and generation development.

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[1] Antares is a sequential Monte-Carlo system simulator developed by RTE. More details can be found in : M.Doquet, C.Fourment,J.M.Roudergues "Generation&Transmission Adequacy of Large Interconnected Power Systems : A contribution to the renewal of Monte-Carlo approaches", PowerTech2011, IEEE Trondheim

[2] Starting grid 2030 based on the actual grid and the TYNDP2014 enlargements (see D2.2 and annex 12 for more details)

[3] Transmission requirement ("TR") : needed increase of capacity between two clusters to solve SoS-issues and/or to optimize dispatch. Transmission requirements are called "reinforcements" in this report as well. They do not presume the technological option and detailed route.

The purpose of the grid development is to minimize the effects of grid limitations at least cost. In that perspective, “transmission requirements” (TR) are defined: they represent the needed increase of capacity between two clusters. At this stage, they do not presume the technological option and detailed route. TRs are also called “reinforcements” in this document.

Given the complexity of the study, the analysis is carried out in two parts :

- The constraints analysis
  It identifies the issues: their significance, their localization and the most critical periods of the year. This enables a focus on the major issues.
- The grid development process
  Transmission requirements are suggested and tested in an iterative process. Once all the reinforcements are identified, they are transposed into possible technologies to assess their cost and verify the profitability of the complete set of reinforcements (called an “architecture”).

Constraints analysis

The set of results at hand in such a probabilistic approach is immense (8760 hours x 99 MC years for each cluster (~100) and each link (>200)). To perform the analysis of this very large database, the process relies on a progressive approach in both time and space dimensions. This approach aims at understanding **where, when** and **how** bottlenecks in the system occur.

The following indicators are analyzed in depth **for each scenario** at different time and geographical scales :

- **ENS** (Energy not served or unsupplied energy) represents the volumes of energy not served due to network limitations. (NB : Given the top-down approach followed to build the scenarios -see D2.1-, it is natural to encounter ENS : the scenario were not built so that countries secure independently their load.)
- **Extra spillage or delta spillage** depicts the must run energy (e.g. Renewables) that cannot be consumed due to the congested grid.
- **Thermal redispatch** :
  - **Positive redispatch** in a given cluster means that local thermal generation is, due to grid constraints, increased to secure the load. This generation (more expensive) substitutes RES energy and competitive thermal generation available in other clusters but that cannot be relieved due to network limitations.
  - Conversely, **negative redispatch** means that thermal generation optimized in the copper plate simulation is, due to grid constraints, reduced. Negative redispatching occurs in countries/clusters with capacities in competitive technologies, e.g nuclear and biomass and mainly countries/clusters with excess of energy.
- **Marginal Cost Variation (MCV) of the links :**
  This indicator (marginal) displays the potential benefits for the system for an extra MW available on a given inter-cluster link. It points out the 1st bottlenecks in the system.

Progressive identifications of the issues

The first analyses focus on the yearly indicators for the whole system to illustrate the overall effect of congestions. Then all indicators are scrutinized at smaller time and space resolution in order to locate and quantify volumes congested.

At the end of this process, specific weeks of interest are selected thanks to their criticality and their representativeness regarding ENS, spillage and redispatch. They are analyzed in average over the 99MC years but also for specific Monte-Carlo years to assess the synchronicity and amplitudes of the phenomenon.

For those weeks, synchronous surplus and deficit areas are identified. "Surplus areas" correspond to area in which there are unused renewable and/or cheap thermal generations that could be released by grid reinforcement. On the contrary, "deficit areas" face ENS and/or positive redispatch due to grid limitations. It is necessary to ensure the synchronicity of those phenomenons as they can occur in different Monte-Carlo years or different periods of the day and thus connecting these areas cannot solve the problems.

3.2. Grid development

Proposal of reinforcements

Once the constraints in the starting grid are identified, transmissions requirements are suggested and tested in an iterative approach:

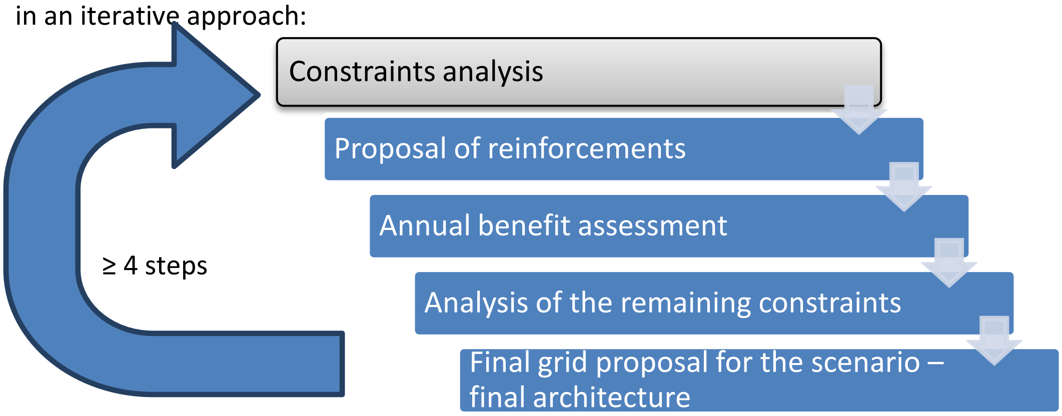

Fig. 1: Iterative process to define the reinforcements

Based on the constraints analysis of characteristic weeks, reinforcements are suggested to connect areas in surplus to areas in deficit. Their sizes are set based on the identification of synchronous volumes at stake. The possibility to collect or distribute energy along the path is considered.

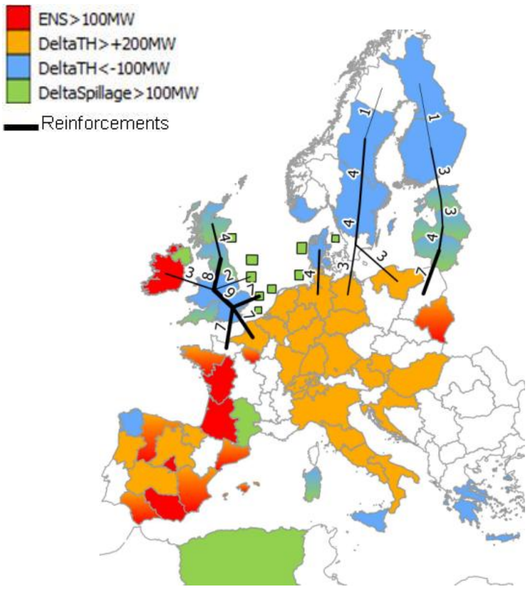

Fig. 2 : Example of map with average hourly values on the 99 Monte Carlo years in a characteristic week and reinforcements

The reinforcements are not tested one by one or all at once : at each iteration of the process, a set of reinforcements (called a "step") is studied. The interest of this approach is to fasten the process but the risk is to over-invest. The "steps" aim at solving only one issue or several **independent** issues, in order to avoid adding, in a same step, redundant reinforcements; especially, the more the issues are in the centre of the continental Europe, the more the reinforcements may have interactions between each others.

During the first steps, the focus is mainly on solving ENS for the most critical weeks. Indeed, ENS has a very high cost and thus reinforcements are likely to be very profitable. Due to this fact, a sensitivity analyses on the profitability of the proposed grid architecture has been executed for two different levels of ENS costs (10 000 €/MWh and 1 000 €/MWh). Moreover, areas with ENS in the most critical weeks usually face high positive redispatch in other weeks and are thus very good candidates for profitable reinforcements over the whole year.

Annual benefit assessment

Grid reinforcements are modelled in the simulations as DC links. Once a set of reinforcements have been tested (and potentially refined) in the characteristic weeks, an annual simulation is performed on the 99 Monte-Carlo years to assess the global impact.

Annual gains on ENS, spillage and redispatch are calculated. The annual benefit of the "step" is calculated as the sum of generation costs savings and ENS costs reduction. Within the project, ENS costs are estimated on the level of 10 000 Euro/MWh for the whole Europe but a cost of 1000 Euro/MWh is also considered in a sensitivity analysis.

The cost of the tested set of reinforcements is then roughly assessed considering only DC cables, as the most expensive case. It is compared with the benefits, to verify that the investments are profitable whatever technology is used – "no regret investments". Some reinforcements may be modified if they are inefficient or over-sized (over-sizing characterized by very small remaining MCV or flows well below capacity).

Based on the remaining constraints in the characteristic weeks, a new iteration of reinforcement is then defined. If there are no more significant issues (which means only small and spread volumes of ENS, spillage and redispatch remain), the iterative process stops.

The final grid proposal is made of all the transmission requirements (reinforcements) defined in the different steps and defines the **final architecture**.

3.3. Technological and cost assessment

As explained previously, Transmission Requirements (TR) are not related to any specific technology as they represent the major grid reinforcement needs. However, they are transposed into possible technologies in order :

- to ensure that there are technical solutions available,
- to better assess the cost of the final architecture.

The selection of technologies in 2050 will be highly impacted by the level of public acceptance towards new lines, this will impact the costs of the architectures. Thus, three strategies are considered to encompass a large range of possible costs :

- **Status Quo** : the public opposition against new infrastructure prevents any new OHLs. Only refurbishment of existing lines or new DC cables can be implemented.
- **Re-Use of Corridors** : the public accepts new OHL as long as they are close to existing lines. Therefore new AC or DC Overhead-lines can be implemented when they are in the existing corridors.

- **New Grid Acceptance** : the public accepts new OHL and also the development of new corridors. DC cables are also possible but OHL are preferred when possible due to their lower costs.

It should be noted that a given transmission requirement can of course be realized through many parallel lines, especially due to the capacity limit of a single line and the N-1 robustness. These different lines could follow different routes between the clusters and be connected to different substations, but this is out of the scope of this report.

The three strategies are only used to have a rough assessment of costs, they do not represent necessarily the best technological solution. Especially, innovative solutions like superconductors, partial undergrounding or higher voltages were not assessed even though they are very promising. Indeed the precision of the study does not allow a complete comparison of the different technological solutions. Therefore an exhaustive discussion of available options and their advantages is made in D 3.2.

A simplified cost benefit analysis is carried out here, while a more comprehensive toolbox is proposed in the dedicated WP6. For the three strategies, the investment annuity[4] of the final architecture is compared to the annual benefit of it, to measure the level of profitability. This assessment of the profitability encompasses the whole architecture and does not evaluate profitability of partial packages of reinforcements (the profitability of each reinforcement depends strongly on the other reinforcements thus it is difficult to assess the profitability of a single project).

3. Grid model

For the system simulations, the European power system is modelled through a hundred clusters as shown in Figure 7. Demand and installed capacities for each technology per clusters within each country has been defined within Scenario Quantification process and presented in Deliverable D2.1.

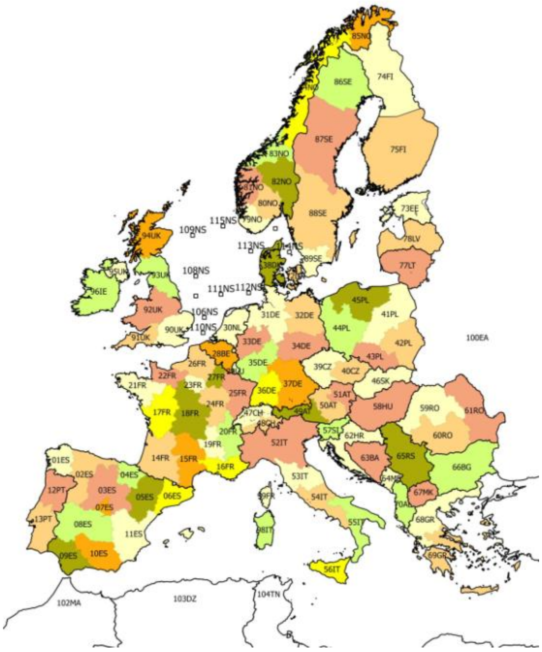

Fig. 3: Countries and clusters + North Sea and North Africa

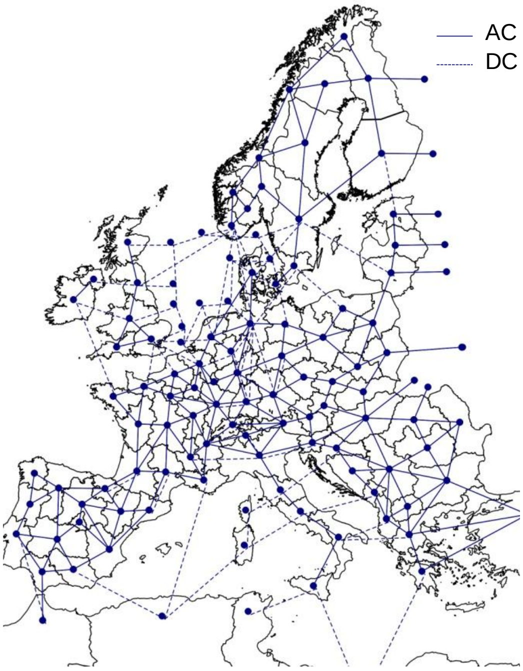

Fig. 4: Equivalent transmission network

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[4] Investment annuity is calculated as discounted annual costs respecting economic lifetime of the equipment defined in WP3 and discount rate of 5%.

As a result of this clustering, the transmission network is also simplified (see Figure 4). Details can be found in Deliverable D2.2. The starting grid has been derived from ENTSOE-e CIM dataset. In it, in addition to today situation (2015), already significant investments that will be included up to the year 2030 are considered, for example:

- HVDC corridors in Germany and southwest France, from UK to continental Europe and UK to France,
- AC reinforcements in central Europe and Baltic states

More details on the projects included are given in Appendix. These reinforcements are not reevaluated.

Connections with North Africa

Connections from North Africa to Europe are considered as already in service, their development is out of the scope of the e-Highway2050 project. Other studies have been launched to perform an assessment of their interest : Desertec initiative, Medgrid, MedTSO.

Connections with North Africa have capacities that depend on the scenario (according to the assumption of Solar Power development in North Africa).

Connections with clusters of wind farms in North Sea

The capacities of the links to connect the offshore clusters are assumed to be only around half of the installed off-shore wind capacities since further development of North Sea connections with UK, continental Europe and Nordic countries (in the form of meshed grid connections or not), is analysed in the project.

4. Cross comparison of the scenarios

The five e-Highway2050 scenarios were defined to encompass a wide range of possibilities. As a result, they have very different levels of demand, types and localization of generation. It results in different transmission requirements but nevertheless, common conclusions can be drawn.

5.1. Demand and generation in the scenarios

Demand

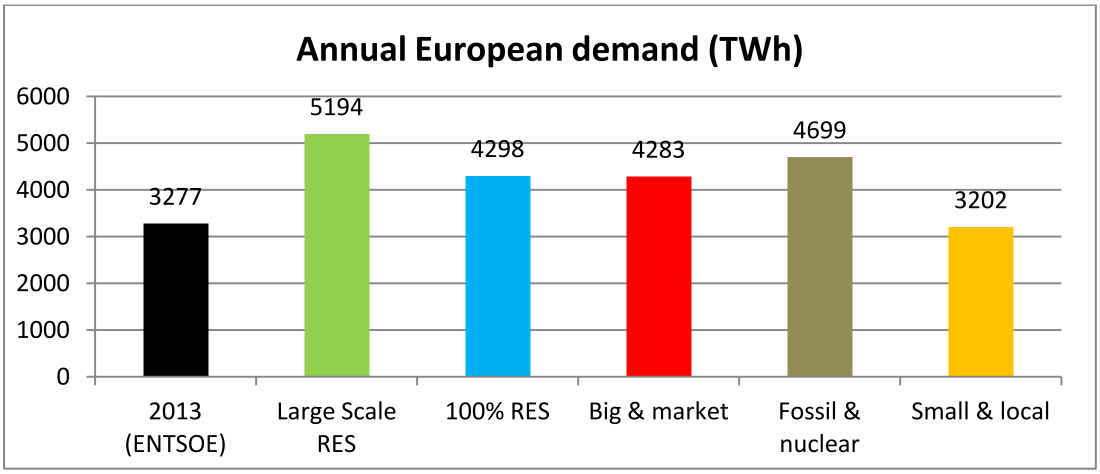

Fig. 5 : European demand in the scenarios

The European demand varies significantly between the scenarios. The scenario *Small & local* has the smallest one (3200 TWh), close to the 2013 level (3277 TWh). On the contrary, the demand in the scenario *Large Scale RES* (5200 TWh) is almost doubled in comparison to 2013. The three other scenarios are in between.

European energy mix

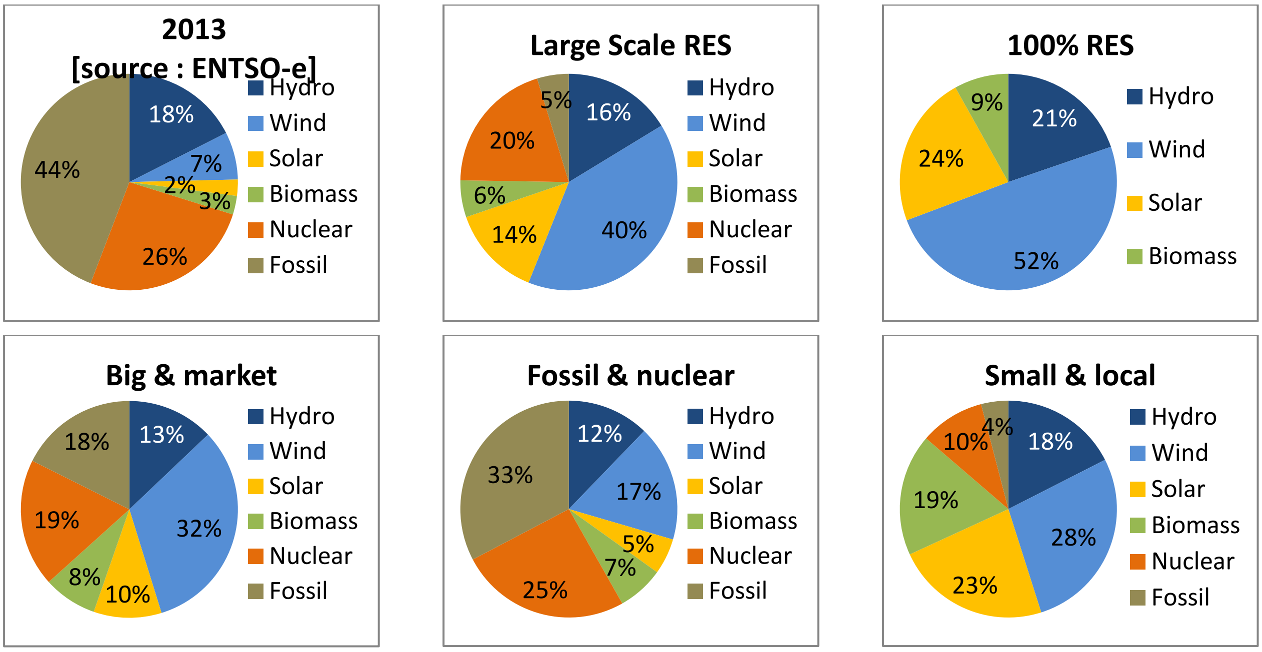

Fig. 6 : energy mixes in the scenarios and in 2013

The share of renewable energy sources varies from 40% to 100% in the different scenarios. Wind generation is especially significant in scenarios *Large Scale RES* and *100% RES* with 40-50% of the generation. Solar plays a major role in the scenarios *100% RES* and *Small & local* with around 25% of the total generation.

Nuclear represents 20% or more of the total generation in three of the five scenarios: *Large Scale RES*, *Big & market* and *Fossil & nuclear*. Indeed, nuclear helps to achieve the EU target to reduce CO2 emissions by 95%. The scenario *100% RES* is nuclear free.

Fossil energy sources are significant in the scenarios *Big & market* and *Fossil & nuclear* with respectively 20% and 30% of the generation. Indeed, in those scenarios the technology of Carbon Capture Storage (CCS) is assumed to be mature. The share of fossil generation in the other scenarios is below 5%.

European installed capacities

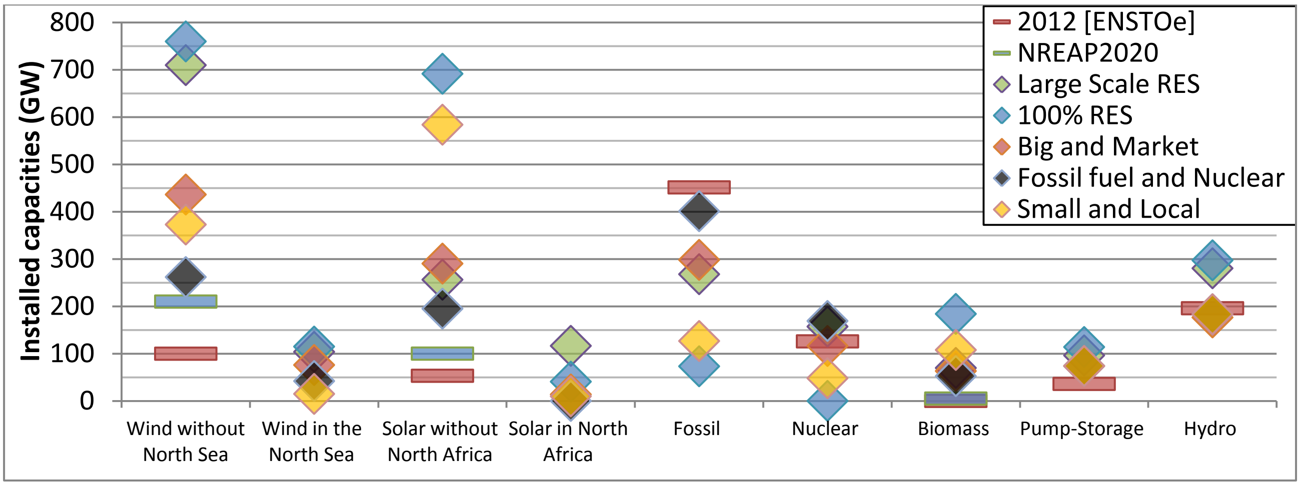

Fig. 7 : European installed capacities in the e-Highway2050 scenarios

The installed capacities of renewable significantly increase in all the scenarios compare to today. Wind capacity ranges between 270GW and up to 900GW with a capacity in the North sea from 15GW to 115GW. For PV, the capacities go from 190 to 690 GW in Europe. Solar generation in North Africa is very high in the scenario *Large Scale RES*, it covers 7% of the European demand for an installed capacity of 116GW. In the scenario 100% RES, it covers 3% of the European demand and less than 1% for the other scenarios.

Fossil thermal capacity decreases compared to 2012 in all the scenarios.

Nuclear capacity increases compared to 2012 in the scenarios *Fossil & nuclear* and *Large Scale RES* up to 169 GW and 157 GW. It decreases in the other scenarios.

Installed capacities per country and copper plate imbalances

Figure 8 to 13 present the installed capacities, the average demand and the copper plate imbalance for each country and each scenario. Values for 2013 are also given for comparison (ENTSOE data). The imbalances are defined as the ratio between the annual generation and demand of the country.

Some countries are net exporters over the year in all the scenarios, this is for example the case for Sweden, Norway, Finland, Romania, Bulgaria and Greece. These countries combine high RES potentials and relatively low demand. On the contrary Spain, Italy, Germany, Belgium and the Netherlands are importers in all the scenarios due to their high demands compared to their local RES resources. For countries like France, UK or Poland, the balance depends on the scenario

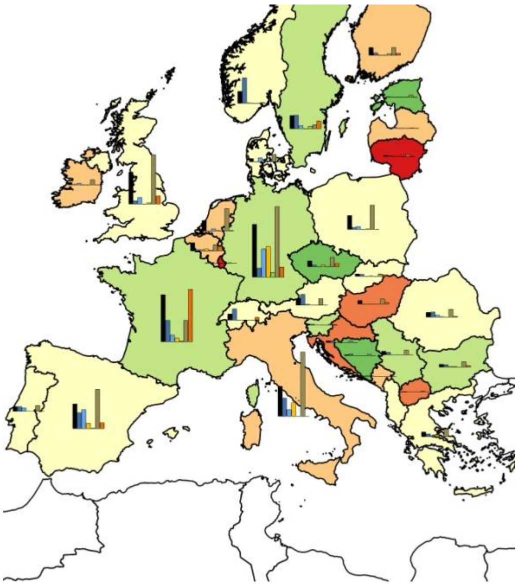

Fig. 8 : 2013 installed capacities and imbalances [ENTSOE]

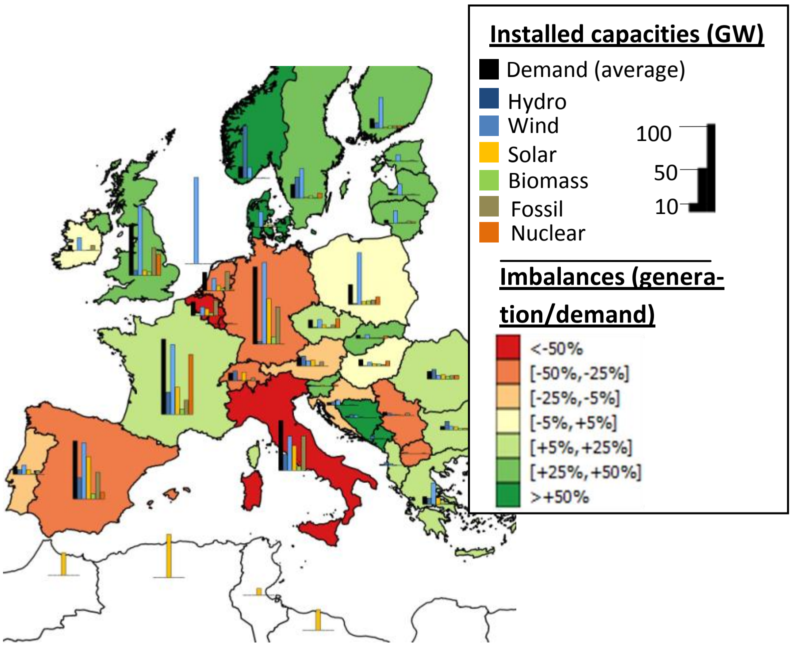

Fig. 9 : Large Scale RES - installed capacities and imbalances

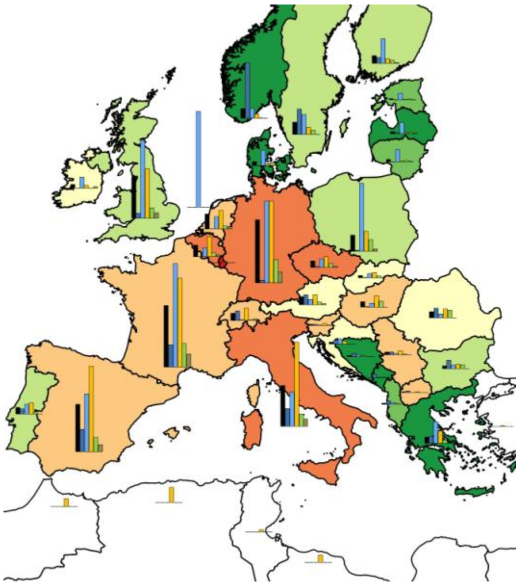

Fig. 10 : 100% RES - installed capacities and imbalances

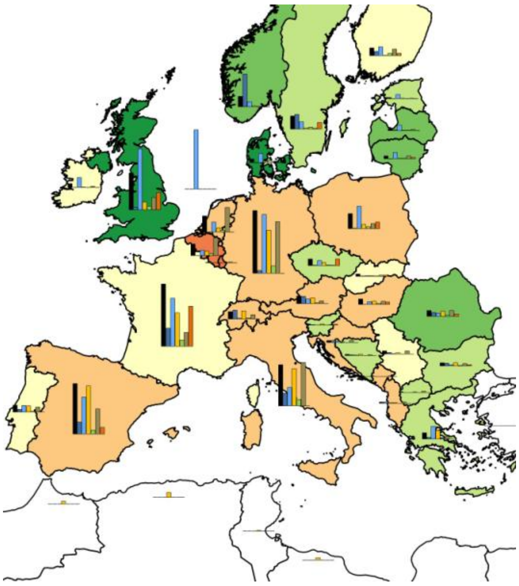

Fig. 11 : Big & market - installed capacities and imbalances

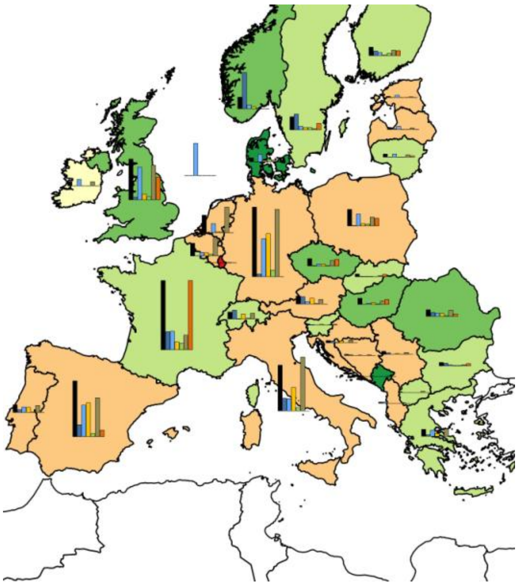

Fig. 12 : Fossil & nuclear - installed capacities and imbalances

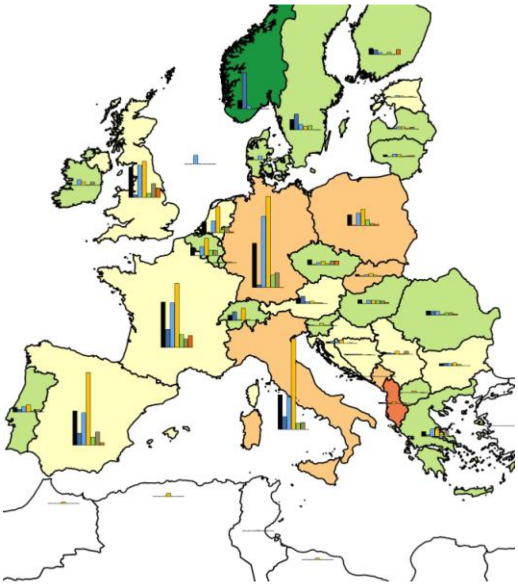

Fig. 13 : Small & local - installed capacities and imbalances

5.2. Cross analysis of the level of constraints in the starting grid

Annual overview for Europe

The following tables and figures summarize the differences between the copperplate and the starting grid simulations for the five scenarios in terms of annual volumes and costs, in other words the impacts of the limitations induced by the existing network capacities. Values from the copperplate situation are used as reference case and considered as the optimal situation in terms of security of supply and operation costs.[5]:

Table 1 : Difference in generation dispatching between starting grid and copperplate (annual values)

Per year	Large Scale	100% RES	Big &	Fossil &	Small &

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[5] Given Values in this chapter can be understood as $Value_{Starting-Grid} - Value_{Copperplate}$

	RES		market	nuclear	local
Energy not served (TWh)	23,4	50,7	11,5	6,8	4,5
Loss of load duration (hours)	3200	3866	3913	2366	1883
Extra spillage (TWh)	571	565	203	42	53
Gas re-dispatch (TWh)	+564	+176	+240	+21	+68
Nuclear re-dispatch (TWh)	-91	-	-69	-31	-11
Biomass re-dispatch (TWh)	+45	+333	-33	-31	-10
Coal re-dispatch (TWh)	+22	-	+53	+81	+1
Extra CO2 emissions (Mt)	211	82	62	38	24
Increase of operating cost (b€)	87	43	26	12	10
Increase of total cost with an ENS cost of 10k€/MWh (b€)	321	550	141	80	56

The annual loss of load duration in the copper plate case is less than 3 hours in all the scenarios, but the grid limitations of the starting grid result in values from 1900 hours in the best case (*Small & local*) to more than 3000 hours in the worst cases (*Large Scale RES*, *100% RES* and *Big & market*). The corresponding energy not served ranges from 5 TWh (*Small & local*) to 51 TWh (*100% RES*). Assuming a cost of ENS of 10 000€/MWh, it means an extra-cost for the system from 45 b€ to 500 b€ per year.

Grid limitations are responsible for an increase of spilled generation. It is limited to around 50TWh in the scenarios *Fossil & nuclear* and *Small & local*, but it goes up to more than 500TWh per year in the scenarios *100% RES* and *Large Scale RES,* representing around 10% of the European annual demand. The increase of the operating cost due to the non-optimal dispatch ranges from 10 to 87 b€ per year.

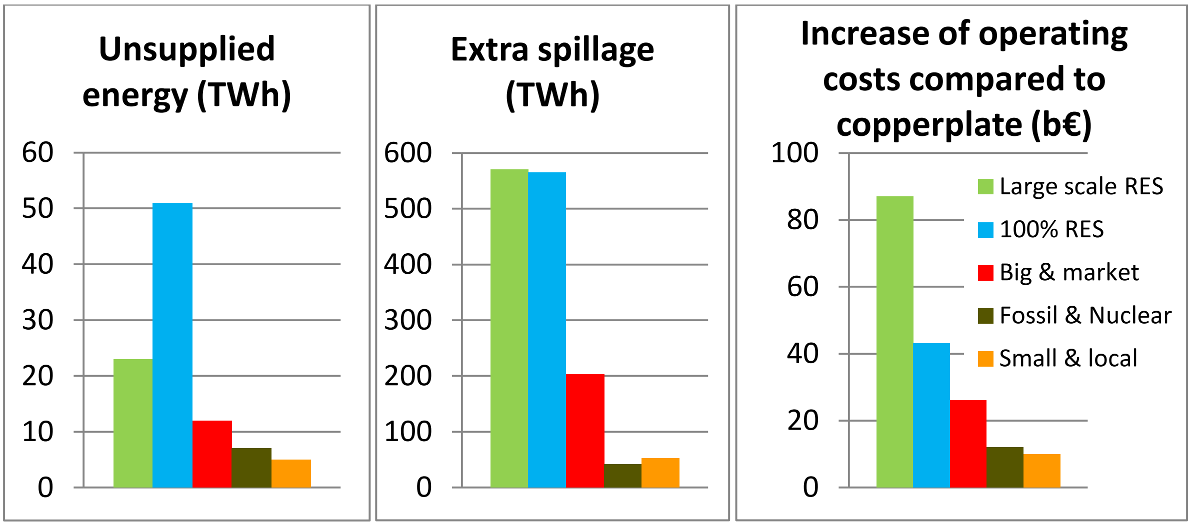


Fig. 14 : Unsupplied energy, extra spillage and increase of operating costs in the different scenarios, before grid reinforcements

100% RES is by far the most critical scenario regarding ENS. *Large scale RES* is very critical as well due to high load, spillage and redispatching costs. ENS is also significant in this scenario. *Fossil & nuclear* and *Small & local* face smaller but still significant issues.

Main deficit and surplus areas

Table 2 presents the main countries in deficit (facing ENS and/or positive redispatch due to grid constraints) and the main countries in surplus (facing extra spillage and/or negative redipstach due to grid constraints) through the different scenarios. It should be noted that a country can be a net exporter over the year and still lacks power during some periods and thus be called an "area in deficit". Similarly, a country can be both "in deficit" and "in surplus" as those phenomenons can occur during different periods.

Table 2 : Summary of the main deficit and surplus countries in the scenarios

			ES	DE	IT	PL	FR	UK	GR	SE	NO	NS
Large scale RES	DEFICIT	ENS	🟥	🟥		🟥						
		Redispatch +		🟧	🟧							
	SURPLUS	Extra spillage							🟩	🟩	🟩	🟩
		Redispatch -					🟦	🟦		🟦		
100% RES	DEFICIT	ENS		🟥		🟥	🟥	🟥				
		Redispatch +	🟧	🟧	🟧		🟧					
	SURPLUS	Extra spillage					🟩		🟩	🟩	🟩	🟩
		Redispatch -										
Big & market	DEFICIT	ENS	🟥				🟥					
		Redispatch +	🟧	🟧	🟧							
	SURPLUS	Extra spillage						🟩			🟩	🟩
		Redispatch -					🟦	🟦		🟦		
Fossil & nuclear	DEFICIT	ENS	🟥		🟥		🟥					
		Redispatch +	🟧	🟧	🟧							
	SURPLUS	Extra spillage									🟩	🟩
		Redispatch -					🟦	🟦		🟦		
Small & local	DEFICIT	ENS		🟥	🟥		🟥					
		Redispatch +	🟧		🟧		🟧	🟧				
	SURPLUS	Extra spillage	🟩		🟩						🟩	🟩
		Redispatch -										

Spain and Italy are in deficit in all scenarios, they face high level of ENS and/or positive redispatch. Italy is an importing country in all the scenarios due to a limited potential of wind generation and no nuclear generation. Spain is more balanced than Italy, but is a net importer as well in almost all the scenarios. This is mainly due to a very high Spanish demand in comparison to today's level. Spain and Italy being peninsulas, they can receive a limited support from the rest of Europe in the starting grid, as a result, they face high ENS and positive thermal re-dispatch. The situation is the most critical for Spain which is less inter-connected.

In the scenario *Small & local*, Spain and Italy are also in surplus due to high PV generation around mid-day.

Germany is an area in deficit in all the scenarios. Indeed, Germany has a very high demand which cannot be satisfied locally if CO2 emissions are reduced and nuclear phase-out is assumed. It imports energy from

North sea clusters and from the rest of Europe in all the scenarios. The grid limitations in the starting grid thus result in ENS and positive redispatch. However, being in the centre of Europe and close to main energy sources (North Sea and Scandinavia), the situation in Germany is less critical than in Spain and Italy. This is also true thanks to the North-South DC corridors in Germany (assumed in the starting grid) which transport energy from the north to the south of the country.

France is in surplus in the scenarios with a high level of nuclear generation (*Large Scale RES*, *Big & market*, *Fossil & nuclear*). Indeed, France has the highest nuclear capacity in Europe and cannot export it if interconnections are not sufficient. However, France is also in deficit in four of the five scenarios, mainly due to high peaks of demand in winter. The interconnections in the starting grid are then non sufficient or internal constraints appear.

UK is a major area in surplus in the scenarios with a high level of nuclear generation (*Large Scale RES*, *Big & market*, *Fossil & nuclear*). Indeed, UK then combines very high wind and nuclear generations which could be exported to continental Europe if the interconnections were less limited.
In the scenarios with less or no nuclear, UK is in deficit during certain periods even if it is not a net importer over the year. The critical periods occur when local generation (mainly wind) is not sufficient to cover the demand : the limited interconnections with continental Europe then do not allow enough imports.

Norway and Sweden are major countries in surplus in all the scenarios. Indeed, they have a rather limited demand but a very high hydro generation and also some wind generation. In Sweden, nuclear plants are also assumed in some scenarios.

The **North Sea** offshore clusters are of course in surplus in all the scenarios. Indeed, they have to export all their generation but the starting grid assumes connections to the shores up to around only half of their generation capacity. The increase of these connections is part of the study.

Other countries face less significant issues or are critical in only one scenario.

Seasonal and cluster overview

Figures 15 to 19 present the major issues at cluster level for one of the most critical winter week for all the scenarios. Figures 20 to 24 give an overview of the issues in a summer week for all the scenarios. They emphasize and refine the conclusions drawn at country level in the previous section.

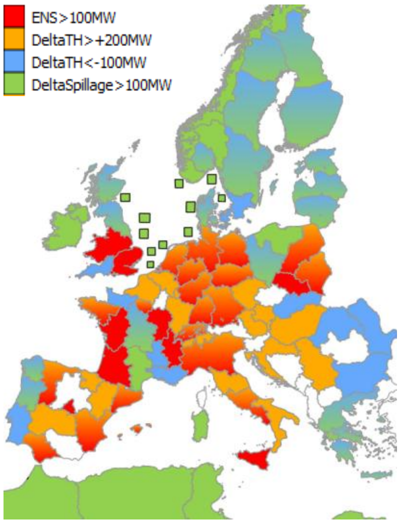


Fig. 15 : Large Scale RES - constraints in the starting grid for a winter week

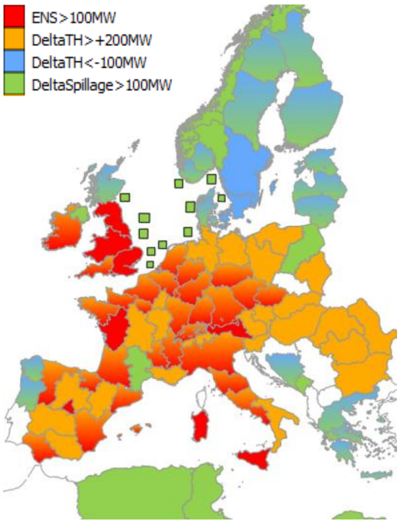


Fig. 16 : 100% RES - constraints in the starting grid for a winter week

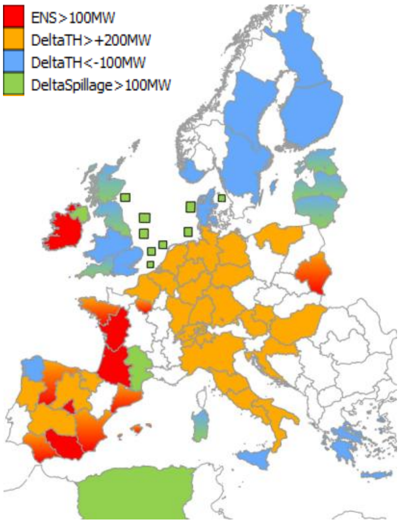


Fig. 17 : Big & market - constraints in the starting grid for a winter week

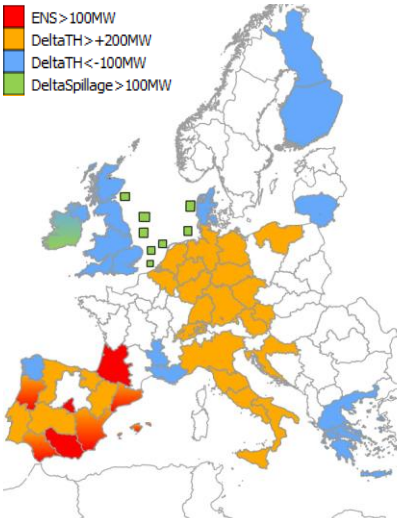


Fig. 18 : Fossil & nuclear - constraints in the starting grid for a winter week

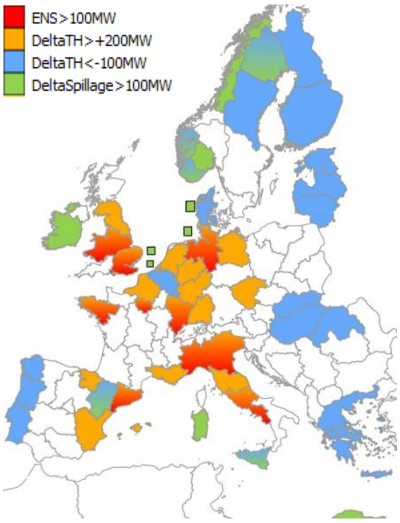


Fig. 19 : Small & local - constraints in the starting grid for a winter week

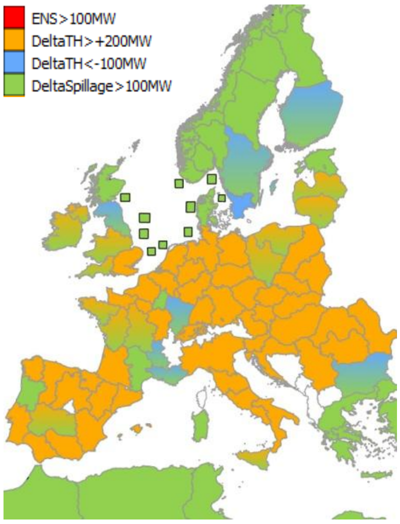


Fig. 20 : Large Scale RES - constraints in the starting grid for a summer week

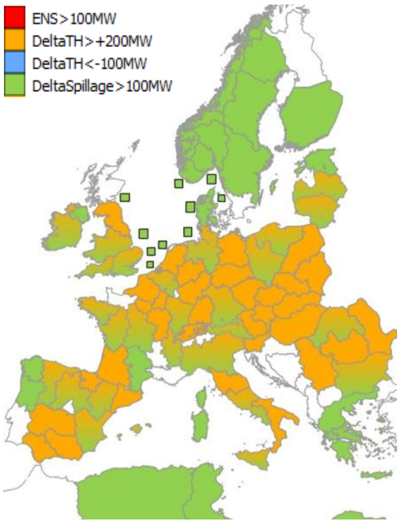


Fig. 21 : 100% RES - constraints in the starting grid for a summer week

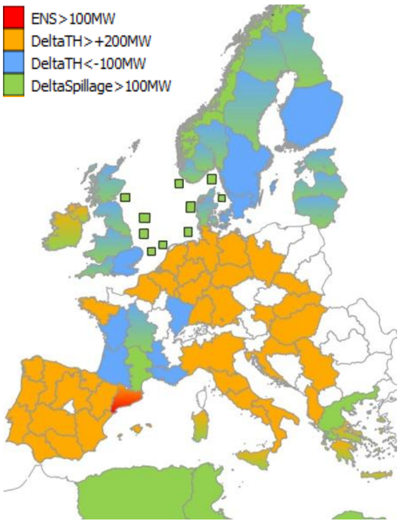


Fig. 22 : Big & market - constraints in the starting grid for a summer week

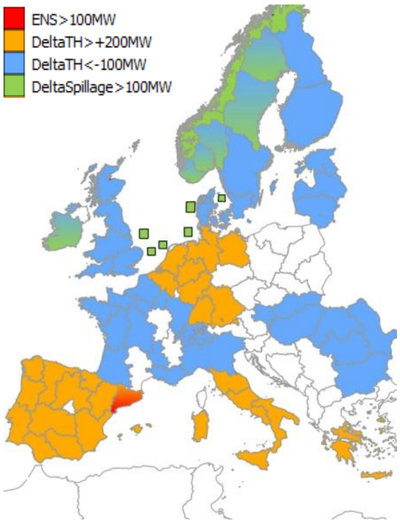


Fig. 23 : Fossil & nuclear - constraints in the starting grid for a summer week

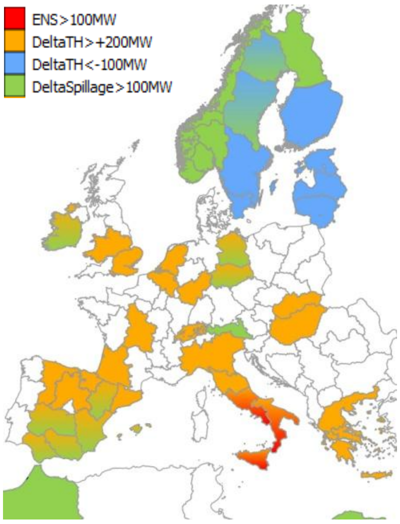


Fig. 24 : Small & local - constraints in the starting grid for a summer week

NB: in summer, it can be noticed that some clusters face both spillage and positive thermal redispatching which seem conflicting. Actually, these two phenomenon do not happen at the same period of the day : spillage occur around midday due to high PV generation whereas positive redispatch occur the rest of the time.

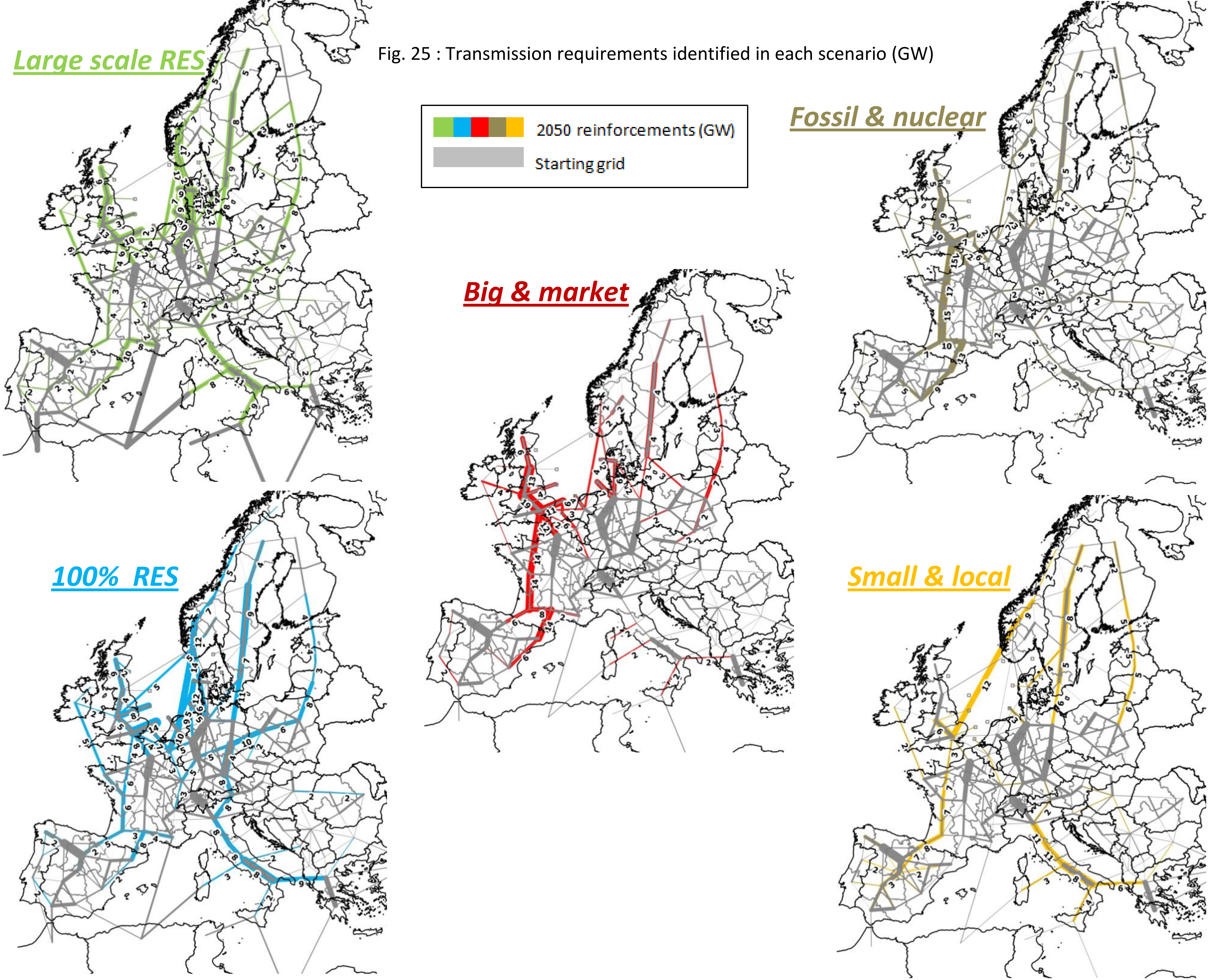
5.3. Final architectures and common corridors

Figure 25 provides an overview of the transmission requirements developed in each scenario .

At first glance one can easily identify the predominance of “North to South” corridors. Indeed in all scenarios there are a lot of reinforcements that collect energy from the north of the system (North Sea, Scandinavia, UK, Ireland) to transport it to the continental synchronous area (northern Germany, Poland, Netherlands, Belgium and France) with opportunity for submarine routes. Major corridors also enable to collect energy from Southern countries like Spain and Italy but also to support these countries with the generation coming from the North.

As foreseen in the analysis of the constraints the scenarios *100%RES* and *Large Scale RES* induce much more transmission requirements (size and distance) than *Small & Local* and *Fossil Fuel & Nuclear* scenarios. *Large scale RES* and *100% RES* show important needs in major infrastructures in the middle of the continental system on top of the peripheral network required in all scenarios : the volumes of renewable in both scenarios, especially coming from North Sea, are such that full corridors from these sources to major load centers need to be reinforced.

Fig. 25 : Transmission requirements identified in each scenario (GW)



The following map (Fig. 26) presents the similarities between scenarios only keeping the corridors that have been reinforced in at least two scenarios. The map also displays a reminder of the range of the size of the corridors developed.

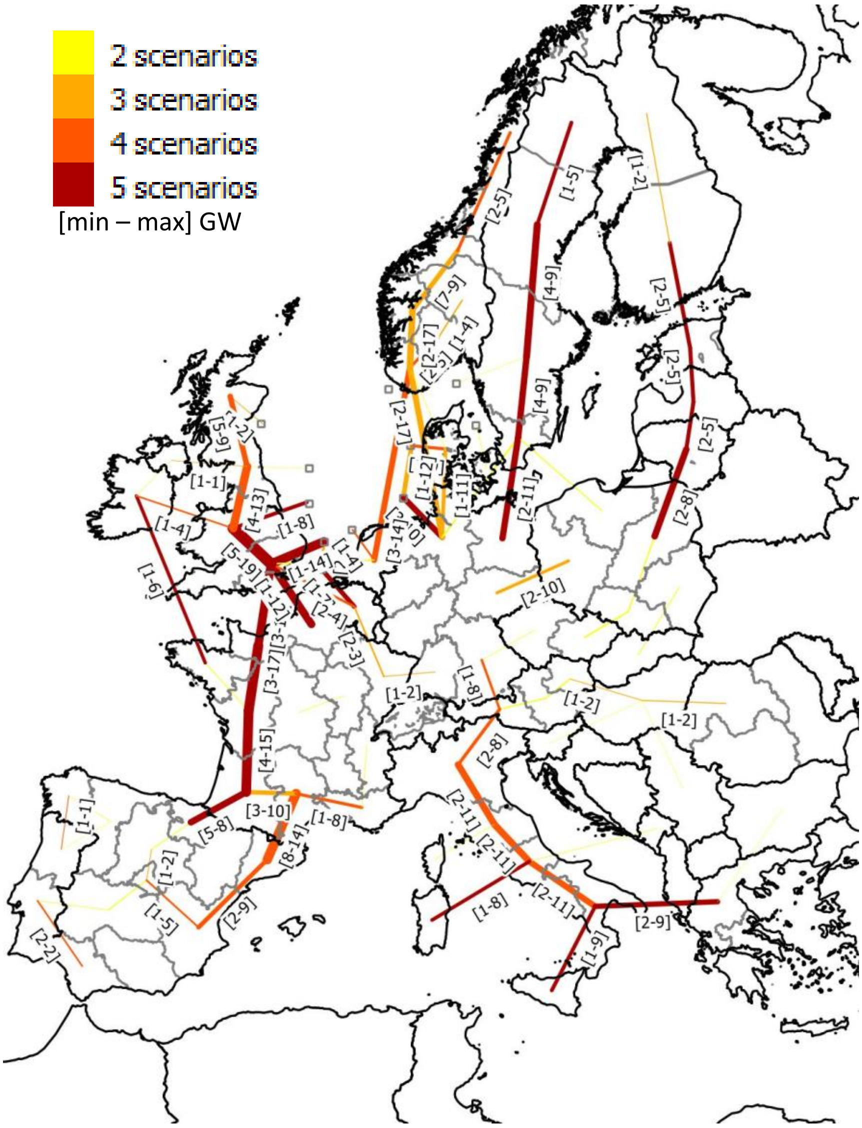


Fig. 26 : Common reinforcements (widths are according to average reinforcement capacity ([Cap (X5) + Cap (X7) + … + Cap (X16)]/5 and the color represents the number of scenarios where the reinforcement is needed)

Nota Bene: A Transmission requirement (“TR”) provides the needed increase of capacity in a given corridor with the purpose to solve SoS issues and/or to optimize dispatch. Sometimes more than one path[6] is possible to provide the same objective, a mix of different paths is even possible. However, the definition of the optimal path was not possible in the e-Highway project due to the geo-

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[6] The meaning of « path » here is the list of clusters which are linked to provide the transmission requirement. For example, the most direct path from Greece to North Italy is to go from South to North Italy (link the following clusters : 68_GR - 55_IT – 54_IT – 53_IT – 52_IT), but another path could go through Balkan clusters and Slovenia.

graphical scale of the study and the related uncertainties on cost. As a result, it may be possible to identify other paths than those suggested in the study that fulfill the same needs and are cheaper or more feasible.

Figure 26 highlights the common need of reinforcements among the scenarios. Hereafter, the significance and behaviour of these corridors are analysed on average flows (over 99 Monte Carlo years simulations). Even if a TR is said to be used, in average, on a yearly basis from North to South for instance, that does not mean the link is never used the opposite way (it very often is the case). Priority has been set on highlighting the structural use of the TR to enable a synthetic understanding and comparison.

From Scotland, down to London area.

Except for the scenario S*mall and local*, in all other scenarios, wind generation from northern UK and North Sea as well as nuclear power (when any) and Norwegian support in *100%RES* scenario, are collected and brought to the main load centres (Birmingham and London areas) and to continental Europe.

Flows are globally unidirectional: North to South, with maximum values reached in winter with a total flow ranging from 8 (*100% RES*) to 15/19GW (*Big and Market*) ***in average*** all day.

In the S*mall and local* scenario no major reinforcement is implemented in Scotland or northern England due to limited wind and nuclear installed capacities. Support from Norway is directly injected in main load area (Birmingham and London) with additional 6GW extra capacity from north used to secure the supply mainly in winter.

Between UK and France

The reinforced link (South-east England to Normandy : + 3GW in *Large Scale RES* up to +15GW in *Fossil & Nuclear*) is used in both directions but with a clear predominant southbound flow, with even some congestion[7] (from 10 to 30% of the year). Maximum flows between UK and France occur in winter (from 2GW up to 12GW in average) bringing support from UK to continental Europe. The link is used northbound, or at 0-flow, in spring especially at midday when PV generation in continental Europe is at its maximum. In S*mall and local* and *100% RES* scenarios where PV volumes installed are maximum, France to UK flows can also be observed at noon in summer and even at noon in winter for *Small and local*. Additional capacity is also developed between UK and the northern French cluster (+3GW to +12 GW). This link behaves as the link described here before. It is very often congested southbound (40% in average in all scenarios). Reverse flows are rare, except for the *Small & local* scenario.

Through Western France

Between Normandy to Aquitaine (clusters 22, 17 and 14 in France) the extra grid capacity developed ranging between 4 to 17 GW depending on the scenarios, is used mainly southward especially in winter. Smaller flow or even an inversion of flows is observed in spring and summer especially around midday.

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[7] When the link is used at its full capacity

Between clusters 14 and 15 in France (South West), an additional capacity ranging from 3 to 10 GW is developed in 3 scenarios (*100% RES*, *Big & Market*, *Fossil & Nuclear*). This capacity is used almost exclusively from 14 to 15 with biggest flows encountered in *Big and Market*, *Fossil Fuel & Nuclear* scenarios in winter and summer when load in Catalonia needs to be secured. In *100% RES* this link is used both ways from west to east in winter and in the opposite direction when PV is high in Spain and North Africa.

Given the size of the corridor added across France in scenario *Big and Market* and *Fossil fuel & nuclear*, one could wonder if this 14-17 GW corridor could be put for instance in the sea with no required interaction with the French clusters along the way. Actually, part of it could but at least 50 up to 70 % should go through these clusters to enable positive/negative injection from existing AC grid. In summer, mostly positive injections from existing AC grid to the corridor are at stake, meaning extra competitive generation from these French cluster join English support towards Spain. In winter, large volumes flowing on the corridor need to be injected in to secure the load, especially in scenario *Fossil and nuclear*, for instance in central west France (cluster 17).

Between France and Spain

The reinforced corridor in the west ([+5 GW; +8GW] is used in average from France towards Spain, but congestion can occur in the opposite direction as well. Maximum southbound flows are observed in summer outside midday. Indeed, at this period, there is no or few solar generation in Spain but there are available wind and/or nuclear generation in the north of Europe which cannot be completely consumed there as it is the case in winter, due to a smaller load. As a result, this cheap generation is exported to Spain to avoid the start-up of local expensive thermal generation as it is done in winter. Maximum northbound flows are measured in Spring at midday (PV surplus sent up north). In the scenario *Small & local*, these northbound flows to avoid PV spillage in Spain are the main drivers of this reinforcement.

The interconnection Spain-France is reinforced on the ***eastern border*** in all scenario but Small and Local [+8GW to 14GW]. It is intensively used southbound with maximum flows in summer (same explanation as the previous one), and in winter especially outside the midday period (9 GW in average) to serve load of Catalonia. Flows are minimal in spring, especially at noon, and may even go from Catalonia to France in *100%RES* scenario and *Small & local*.

Inside Spain: Catalonia (cluster 06), central east (cluster 11), Madrid (cluster 07).

In all scenarios, a 2 GW up to 9 GW capacity is added between Catalonia and central east Spain.

This capacity is used in both directions in all 4 scenarios. Nevertheless in 100% RES the link is predominantly used northbound (towards Catalonia; almost 100GW of additional PV in Spain). Otherwise the link is used southbound in winter and summer especially outside noon and in the opposite direction in spring.

The additional capacity between Madrid and Central East (especially in *Large Scale RES* and *Fossil Fuel and Nuclear* where 2 and 5 GW are added) is used in both directions : from Madrid to Central East when PV is high, in the opposite direction especially in *Fossil Fuel & Nuclear* scenario in winter, to secure load in Madrid.

It can be surprising that no major south to north flows occur in summer around midday in the scenarios with high PV generation. Actually, it should be noted that, in those cases, there is already a significant PV generation in the centre of Europe and especially in France resulting in average to a couple of GW of spillage in these countries around midday. As a consequence, the PV generation in Spain is spilled as well and is not transported to the North.

It should be noted that in all the scenarios, the demand increased significantly more in Spain than in the other countries. This is due to the historical trends used to estimate the national demands. This high demand leads Spain to import electricity thanks to major North to South flows. Lower assumptions for the Spanish demand would result in the predominance of South to North flows to export PV surplus from Spain to the North of Europe, especially in spring and fall. The Spain-France-UK corridor would then still be very profitable, however its size in the scenarios with limited PV (Big & market and Fossil & nuclear) can be reduced.

Ireland-UK- France

The level of installed capacity in wind farms in Ireland together with the load increase are the clear driver for the level of interconnection between Ireland and UK or France.

These links enable the Irish wind generation to reach load centres in continental Europe and UK, but also to secure the Irish load, in case of no wind.

In all scenarios the links developed are used in both directions, in average energy flows from Ireland to France or UK, in winter, and in the opposite direction in spring and summer (especially around midday), when wind in Ireland weakens and PV in the south of Europe is high.

Sweden to continental Europe

In all scenarios, the corridors reinforced inside Sweden accommodate North to south flows, that are maximal in winter and summer when energy is needed south (SoS, and optimal dispatch). Sweden is indeed a clear surplus area in all scenarios.

South to north flows occur in early spring at noon when PV is high in continental Europe (especially in *Small and Local* and *100% RES* scenarios). This is particularly true in southern Sweden. In summer at noon the flows are moderate but remain in average oriented to the south due to significant run of river generation. Hydro generation with reservoir from Scandinavia is shifted to hours when PV is not available, yet generation is needed, especially early mornings and evenings.

The links between Sweden and continental Europe are mainly used southbound with maximum flows in winter and summer (especially outside midday). But opposite flows also occur in early spring when flows can reach in average 3GW (resp 5) between northern Germany and Sweden in scenario *100% RES* (resp *Small and local*).

In the scenario *Big and Market* the link between Sweden and Germany is more used in summer than winter.

Norway to continental Europe and UK

Norway is in 2050 an area with a high potential for export in all scenarios. The level of grid development by 2050 for Norway is naturally led by the installation of new hydro capacity and wind generation. In *Large Scale RES* and *100% RES*, huge capacities are deployed in Norway leading to intensive needs for interconnections (>12GW).

In *Big & Market* and *Fossil Fuel & Nuclear* scenarios, extra connections are significant with a total of 4 to 6 GW additional capacities to northern continental Europe.

In all scenarios except *Big & Market*, reinforcements in northern Norway are necessary from 2 up to 5GW, and used from north to south, with maximum values in winter and summer (average flow of 3000 MW in *100% RES* and *Large Scale RES* scenarios) to bring down hydro generation or wind to the southern clusters in Norway (where the load is), continental Europe or UK.

In *100%RES* (resp. *Small & Local*) a 5GW (resp. 12 GW) capacity is developed to connect southern Norway to central UK. In these 2 scenarios, UK faces risk of shortage or lacks of competitive energy. The link is used from Norway to UK, in winter and summer especially outside midday. Flows are minimal in spring or even reversed at noon throughout the year due to PV generation (in UK and continental Europe) making support from Norway less needed, enabling more pumping in Norway.

In all scenarios except *Small & Local*, Norway's connections to continental Europe (Germany, Netherlands and Denmark) are also increased especially in *100%RES* and *Large Scale RES* where more than 20 GW are added. Southbound flows are maximal in winter and summer (average flows to continent greater than 15 GW). Flows are minimal in spring at midday. For the reinforcement from Norway to North continental Europe, several routes are possible, as illustrated in the different scenarios (through North Sea clusters and/or Denmark and/or none of them; see Nota Bene on the different possible paths on page 18).

Finland – Baltic states - Poland

Large renewable capacities are installed in Finland (hydro, wind generation), Estonia, Latvia, Lithuania (wind and biomass), but also nuclear in Lithuania in 4 scenarios. In the meantime load increases rapidly in Estonia, Lithuania and Latvia (x2).

Transmission requirements estimated in this study enable these areas to export competitive energy to continental Europe, especially to Poland with a potential ranging from 2 to 8 GW of additional grid capacity.

Flows are oriented southbound in average, from Finland to Poland; they grow stronger going through Estonia, Latvia, and mainly Lithuania, collecting available generation along the way. Flows to Poland from Lithuania are maximal in winter in all scenarios.

North Sea

In all scenarios, part of North Sea wind generation is brought to continental Europe to solve ENS and optimize thermal redispatching.

In the initial grid, the capacities of the radial links are only around half of the installed North Sea offshore wind capacities (cf §3) and there is no initial meshing (except the skeleton of a circular meshing with 1MW capacity), in order to enable further radial (from off-shore clusters to on-shore cluster) and/or circular (between off-shore North Sea clusters) reinforcements. As illustrated in the following examples, several paths are possible to reach the same purpose.

Some off-shore clusters with huge volumes of wind power are not close to clusters in deficit of energy. For example, the off-shore cluster near west Denmark is interesting for providing energy to north continental Europe rather than Denmark which doesn't need it. In this case, there are several possible routes to go from off-shore cluster to a cluster with deficit in energy (Germany for example):

- either through Denmark (radial connection to DK + extra capacity DK-DE)
- and/or through a circular meshing between off-shore North Sea clusters (Off shore cluster close to Denmark -> Off shore cluster close to Germany -> cluster in North Germany).

Another example concerns an off-shore cluster close to South UK. A huge part of its wind power is useful for North Continental Europe through Belgium - the path could be :

- either through UK,
- either through a circular meshing between offshore North Sea clusters (offshore cluster close to UK -> Off shore cluster close to Belgium -> Belgium).
- or directly to Belgium.

The optimal choice between those possible paths requires a detailed analysis of the costs, including detailed possible routes. It is not feasible in the e-Highway2050 project.

The reinforcements of radial links Norway off-shore cluster - Norway in *100% RES* and Sweden off-shore cluster – Sweden in *Large Scale RES* and *Fossil fuel & nuclear* aim at collecting North Sea wind generation for continental Europe (through on-shore Norway and Sweden clusters).

Part of North Sea wind generation is brought to UK in all scenarios. In *100% RES* and *Small & Local*, it mainly helps UK which faces risk of shortage or lacks of competitive energy, while in the other scenarios it is further transmitted through UK to continental West Europe.

Finally, all radial links are reinforced at least in one scenario. The total volumes of reinforcement in North Sea ranges between [7GW, 65GW], consistent with wind installed capacity in North Sea for each scenario.

Maximum radial flows occur in winter (when load factor of wind power are maximum).

From Greece to South Italy

In all scenarios, RES and thermal cheap generation from Greece (and North Africa) is brought to Italy to secure load and replace expensive thermal generation.

The extra grid capacity developed for that purpose, ranging from 2 to 9GW, is used mainly from Greece to South Italy, with biggest flows encountered in *100%RES* in winter (8GW ***in average*** all day), when load in Italy needs to be secured. Smaller flows (or even an inversion of flows in *Small & Local* and *Fossil fuel & nuclear*) are observed in summer around mid-day when Italian high capacity of solar is at its maximum.

From Sicilia and Sardinia to South Italy

Except for the scenario *Fossil fuel & nuclear* (which has no connection with North Africa), solar generation from North Africa is brought to Italy through Sicilia and Sardinia to replace expensive thermal generation and only part of ENS (during the periods of highest ENS, at evening peaks in winter, regarding solar, only part of Concentrated Solar Power is still available). Average flows are always northward.

In *Fossil fuel & nuclear*, average flows are always southward to Sicilia and Sardinia to secure Sicilian load and bring cheaper generation to Sicilia and Sardinia coming downward through Italy from eastern Europe.

From South Italy to North Italy

Except for the scenario *Fossil fuel & nuclear*, solar generation from North Africa is brought through Italy northward to supply main cities in the north of Italy and also further in northern Europe.

In the scenario *Fossil fuel & nuclear*, cheaper generation from Eastern Europe is brought downward through North Italy to main cities in Italy (in the north and in the centre).

The Italian backbone is reinforced in all scenarios ([2GW ; 11GW]) but Big & Market which has more cheaper thermal capacity. It is intensively used northbound in *Large scale RES*, *100%RES* and *Small & Local*, with maximum flows in April mid-day to serve load thanks to solar generation from the south. Some congestions occur (up to 30%). In all the scenarios, the northern part of the backbone from North Italy to Tuscany, Umbria and Marches (from 52 to 53) is used southward in summer out of mid-day. This is due to available wind and/or cheap thermal generation in the North and West Europe which can be used in the evening in summer instead of starting expensive thermal in Italy. In winter, this generation is consumed locally and cannot reach Italy.

In *Fossil fuel & nuclear* the northern part of the reinforced backbone from North Italy to Lazio, Abruzzi and Campania (corridor 52-53-54) is used southward in average while the extreme south part (link 54-55) is used northward.

From Austria to North Italy

Between Austria and North Italy, the extra grid capacity developed (except for *Big&Market*), ranging between 2 to 8GW is used in both directions (northward mainly in mid-day periods -solar generation available- in spring and summer). Some congestions occur in both directions (up to 30-50%).

5.4. Cross comparison of costs and benefits

Cross comparison of costs

Figure 27 gives the total investment costs for each scenario as well as their corresponding annuities. For the three less critical scenarios (*Big & market*, *Fossil & nuclear*, *Small & local*), the total cost ranges between 120 and 220b€ depending on the public acceptance of new over-head lines and therefore the available reinforcement technologies. In the scenarios *Large Scale RES* and *100% RES*, the architectures are almost twice as expensive with a total cost around 250 b€ in the case of new grid acceptance and around 390 b€ with DC cables in case of status quo.

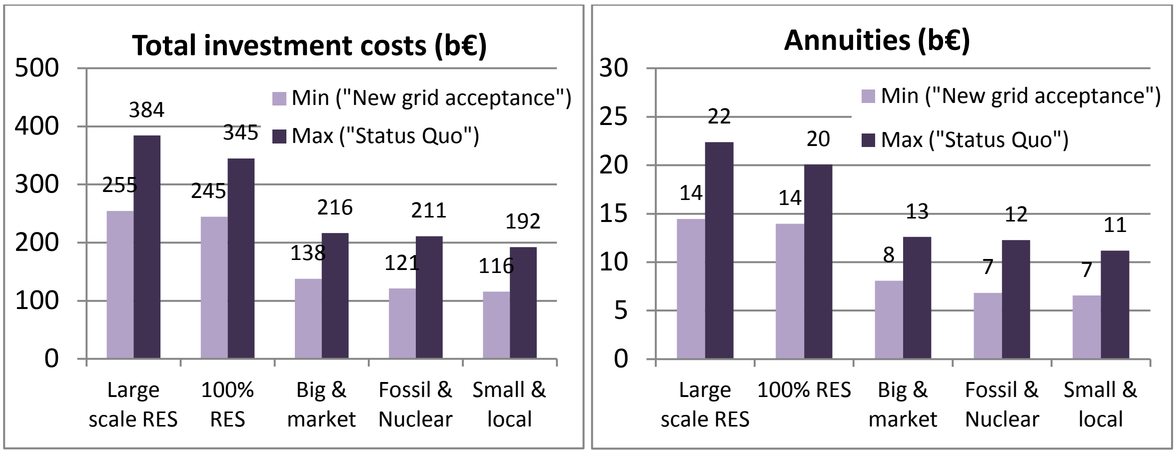

Fig. 27 : Investment costs and annuities of the final architectures for each scenario

Cross comparison of benefits

Fig. 178 compares the benefits provided by the architectures in each scenario, with a focus on SoS, and optimal dispatch.

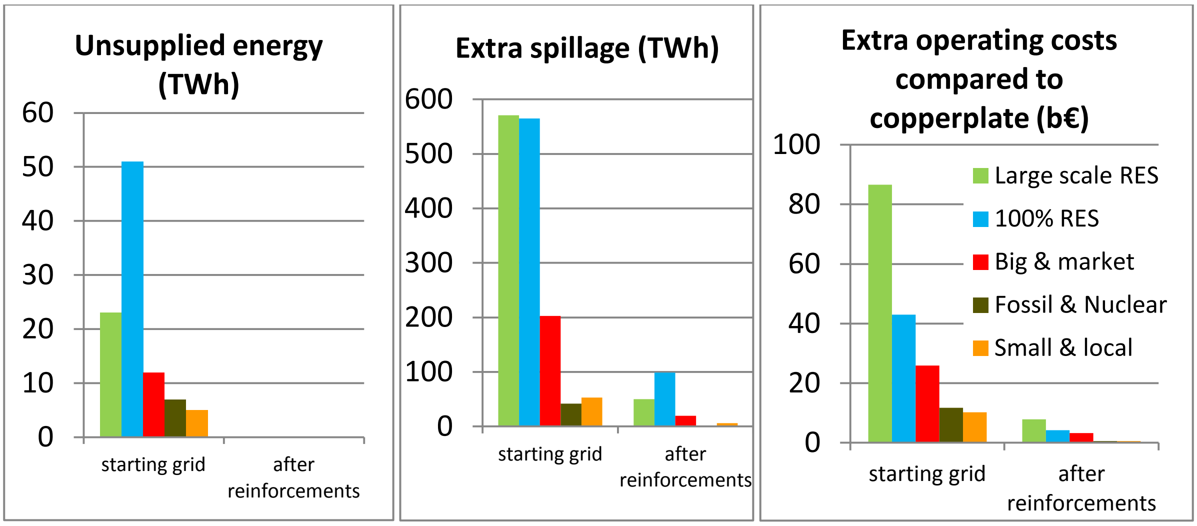

Fig. 28 : Unsupplied energy, extra spillage and increase of operating costs in the different scenarios, before and after grid reinforcements

For all scenarios, almost all ENS has been solved, and generation redispatch has been drastically reduced. Remaining volumes of ENS, spillage and redispatching are very small and spread, which left no room for easy detection of profitable new reinforcements.

Table 3 summarizes the benefits of the grid reinforcements in each scenario. As it can be expected, the benefits are more important in the scenarios which faced the most critical issues (*Large scale RES* and *100% RES*), it corresponds also to the scenarios with the most significant transmission requirements identified. The reduction of ENS goes from 5 TWh (*Small & local*) up to 50 TWh (*100% RES*). It results in an annual benefit of 50-500 b€ for an ENS cost of 10 000€/MWh or 5-50b€ for an ENS cost of 1000€/MWh. Spillage reduction ranges between 40 TWh (*Fossil & nuclear*) and 465 TWh (*100% RES*). Without ENS costs, the reduction of the annual operating cost of the European system (which includes CO2 costs) ranges from 10 b€ (*Small & local*) to 79b€ (*Large Scale RES*) which justifies almost the architectures by itself.

Table 3 : Benefits of the grid reinforcements for each scenario

PER YEAR	Large scale RES	100% RES	Big & market	Fossil & nuclear	Small & local
Reduction of ENS (TWh)	23	51	11	7	5
Reduction of spillage (TWh)	521	465	182	41	47
Reduction of the operating cost (b€)	79	39	22	11	10
Reduction of CO2 emissions (Mt)	192	80	54	35	23
Total annual benefit (assuming ENS=10k€/MWh)	309	549	132	81	60
Total annual benefit (assuming ENS=1k€/MWh)	102	90	33	18	15
Range of total investment cost (b€)	[255-384]	[245-345]	[138-216]	[121-211]	[116-192]
Range of investment annuities (b€)	[14-21]	[14-20]	[8-13]	[7-12]	[7-11]

The total annual benefits in each scenario can be compared to the annuities of investment. Even with the strategy “status quo” (DC cables) and with an ENS cost of 1000 €/MWh, the architectures identified in each scenario are profitable. Assuming a cost of ENS of 10 000€/MWh, the architectures in the scenarios *Large Scale RES* and *100% RES* are even profitable within one year, what is explained by the tremendous amount of congestions. The reinforcements are more significant in those two scenarios - the investment cost is doubled compared to the others- , but they are also much more profitable : their benefits are three to nine times higher.

5. Conclusion

The results provided by this study are two-fold : the methodology applied and the final architectures at 2050.

Methodology

A new methodology for long-term grid development at European level was developed and carried out successfully within WP2. It relies on Monte-Carlo simulations which embed a detail modeling of both the generation and the grid for around hundred clusters in Europe. First, a detailed analysis of the system inefficiencies induced by grid limitations is performed. It points towards critical weeks and areas which are then at the core of the grid development. Reinforcements are suggested through an iterative process. Their benefits are computed from the annual gain in the generation cost and the annual reduction of the unssuplied energy cost. A simplified cost/benefit analysis finally ensures that the complete suggested architecture is profitable even with the most expensive technological solutions.

This methodology proved to be very efficient for long-term studies where the level of generation and demand are completely different from the current ones and its locaton is object to high uncertainties. It enables a real European approach as the whole system is simulated at once and reinforcements are identified considering all the European issues and solutions. The systems simulations performed ensure the robustness of the results thanks to the Monte-Carlo approach and their relevance thanks to the detailed modeling. The methodology was applied successfully by five different partners of the project, proving its feasibility. It could now be applied for studies with different assumptions, time horizon or geographical scope.

Architectures at 2050

The simulations performed during the study of the five e-Highway2050 scenarios showed a high need of transmission grid in 2050 to fulfil the European decarbonisation target : from 50 to 500 TWh of generation is inefficiently used annually without grid investment. The scenarios with the highest renewable generation are those where more reinforcements were identified (up to 400 b€ of investment costs), but they are also those with the highest profitability brought by the grid development (with an ENS cost of 10 000/MWh, the investment can be paid back within one year). This is explained on the one side by the highly fluctuating in-feed of renewables that can be balanced throughout Europe if the grid does support this power exchanges. And on the other hand it lowers the costs of generation thanks to “cheap” production from renewables and not required thermal dispatch. Even in the scenarios with less renewable or with a distributed vision, significant transmission requirements are profitable. These investments don’t take into account the additional reinforcements inside clusters which will be necessary for the proper operation of the system. Nevertheless, these additional reinforcements will be significantly less expensive than the reinforcements between clusters and so they should only slightly reduce the profitability.

Despite the huge differences in the assumptions of the five scenarios, common and significant transmission requirements appeared :

- from Scandinavia to northern continental Europe
- from Finland to Poland through the Baltic states
- from UK to Spain through France
- From Greece to Italy

Even if profitability in 2050 does not mean profitability for today, these reinforcements are for sure good candidates for additional analysis.

It must be pointed out that the defined structures rely on the realization of the projects announced in ENTSO-e’s Ten Years Network Development Plan. The complete development plan has been assumed as available in a starting grid and it cannot be guaranteed that the final grid solutions from e-Highway 2050 are sufficient without them. Especially in the projects that can already be understood as first steps towards an overlay-system, e.g. the HVDC corridors in Germany seem indispensable for a sufficient transmission capacity in 2050. Furthermore, as described above, the aim of the grid development task was to identify the minimal required grid extension that is beneficial under severe circumstances (“no-regret investments”). Beyond those it seems very likely that additional projects can be beneficial, but have not been considered here due to above mentioned reasons. The results must therefore be understood as a *lower bound* for the future transmission system.

Within e-Highway 2050, only the network investment costs are assessed in each scenario. The investment costs for distribution, generation, storage and demand side management are out of the scope of the study but are for sure of interest to get a comprehensive view of the whole electrical system.

Further studies within the project

The results of task 2.3 and the grid development process are further used in other parts of the study e-Highway 2050 to further assess and amend the outcomes. In detail this means:

- **Check for implementation and operation:**
  In **Task 2.4 and 4.1** the developed structures are assessed in terms of the ability to be implemented and operated in the existing 220kV/ 380kV transmission system. It is planned to identify problems in the cluster internal grid and suggest counter measures to enable a safe operation.
- **Identification of R&D Efforts:**
  The main target of task 2.3 was the identification and dimensioning of transmission corridors throughout Europe, which support the existing transmission system. Among the *state-of-the-art* technology 380kV AC several new ones can be suggested, that are not part of the interconnected European system today such are higher AC-voltage levels (550 kV) and DC technologies in ±320kV, ± 600kV. Latter for instance require a meshing and therefore the existing of dc-breakers, which are not maturely available today. **Working package 3** will further discuss these different solutions and determine R&D needs to be addressed to the manufactures.
- **Environmental Impacts:**
  Beside the public acceptance of the new infrastructure it is also expected that environmental issues will play a increasing role in grid development. The effects of the suggested structures and their severity to the environment are analyzed in Task 4.1.
- **Intermediate Steps an modular development:**
  Analyzes in task 2.3 focused on the year 2050 only. It was determined what additional investments are required beyond the TYNDP 2014 starting grid in 2030, depending on the scenario. The development path towards 2050 and the modular implementation of corridors are assessed in **Task 4.3 and 4.4**.
- **Governance model Realization:**
  It was shown that the suggested grid architectures provide a benefit throughout the assumed uncertainties in 2050. Besides the technical points of grid development it is also a question who are stakeholders to finance and operate these systems. **Working Package 5** therefore suggests governance options that deal with these aspects.
- **Comprehensive Costs-Benefit-Assessment:**
  To assess the benefit of new transmission corridors task 2.3 applied a simplified costs benefit analyses where the annual costs of new reinforcements were compared with their benefit in terms of decreased generation costs and prevented energy not supplied. **Working package 6** has developed a detailed methodology to consider further aspects and will use this to assess the costs and benefits of the suggested structures in a entire frame.