e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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Start date	1st of September 2012	**Duration**	40 months
WP 2	**Developing the Grid architecture options as a function of the retained scenarios**		
D2.4	**Contingency analyses for candidate grid architectures for 2050**		

		Date & Visa
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Executive Summary

The purpose of the analyses performed and described in this deliverable was the operational validation of the inter-cluster reinforcements as they have been defined and evaluated in the e-Highway 2050 project. To reach this, the final grid architectures and results from unit commitment optimizations have been included in the starting grid. Latter represents the most realistic status of the European high voltage transmission system as it has been depicted in the Ten Years Network Development Plan 2014 (TYNDP ’14), published by ENTSO-e. Based on this starting situation and the results of the grid development, all five scenarios have been analyzed (either qualitatively or quantitatively).

As a result it has been shown, that the additional costs, involved with the implementation of inter-cluster architectures in the existing system, don’t jeopardize the overall benefit of the grid solution. Depending on the scenario and the strategy followed, the additional costs to ensure safe operation vary between 0 b. € (e.g. AC Strategy in Big & Market Scenario) and 30 b. € (DC-Strategy in Nuclear and CCS Scenario) - what in latter case means a share of 14% of the total investment costs. Thus it was concluded that grid architecture development is a beneficial way towards reaching the European clime Targets.

As a result it has been experiences, that system operation will be challenged in the future by the major changes expected in the European electrical system. Four main sources of change are identified, each having a potential impact on the different operating issues:

- ***The increasing penetration of renewable energy sources:*** RES have radically different behaviors than traditional plants (small power electronics device vs. large synchronous generator). In four of the five e-Highway2050 scenarios, during some hours, they are the only generating units connected to the grid, supplying entirely the European load.
- ***The increasing power exchanges:*** Today, power flows on the transmission grid still occur mainly on a country level whereas major cross-country flows are expected in all the e-Highway2050 scenarios.
- ***The increasing number of connections realized with HVDC:*** HVDC behaves radically differently than AC lines. Today, a few DC lines exist in the European system to connect non-synchronous areas and only one DC link is implemented in parallel to AC lines. In e-Highway2050 scenarios, at least 50 GW of more HVDC are foreseen in addition to the 2030 projects of the TYNDP.
- ***Increased importance of Hubs for bulk-power transport:*** With the increased interaction of the European countries in matters of energy production and security of supply bulk power transmission lines will play a more important role in the future. Also with the increased role share of centralized renewable production this issue arises. These “hubs” must be integrated in the existing transmission system.

The analyses show, that the implementation of AC reinforcements leads to less overloads throughout all scenarios and snapshots than DC reinforcements. AC lines are “passive” grid elements and the flow they are utilized with is a direct result of the physical parameters and the topology of the whole synchronous transmission grid. Therefore the flows “adapt” automatic to new conditions. On the contrary DC elements are controllable and an operation strategy can be defined for them. This

means that, by default, flows in these elements do not adapt to new situations but remain within pre-set parameters. The operation strategy of these elements has therefore a high impact on their implementation in the existing system. In the current state this can lead to in-efficient operation causing more constraints. New operation strategies may improve this situation, but there development was not in focus on the analyses performed here.

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1. Introduction

The aim of the study e-Highway 2050 is the definition of target grid structures in the year 2050 that allow reaching the European climate targets. In the first task 2.1 (Data sets of scenarios for 2050) energy scenarios have been quantified which describe the load and the generation situation in the five e-Highway scenarios and lead to a reduction of carbon dioxide emissions in 2050 of 80% to 95% (compared with 1990). In task 2.2 (European cluster model of the Pan-European transmission grid) a cluster model of the (in 2030) existing electricity transmission grid has been determined and is then used as the starting point for further analyses. Task 2.3 (System simulations analysis and inter-cluster -grid development) identified target capacities and transmission corridors throughout Europe that need to be established until 2050 in order to provide a grid that is capable of realizing security of energy supply and competitive energy prices. Additionally three strategies were developed to build these architectures by assuming different levels of public acceptance for new grid infrastructure, thus affecting the possibilities for the use of technologies to realize the required transmission capacities. Based on these technical solutions it was possible to assess the costs – minimal and maximal – of the target architectures and determine the overall benefit of each of them.

The result of task 2.3 was five different target architectures – one for each scenario- and 3 different technological ways to realize each of them. It was shown by task 2.3 that these structures, independently from their technical realization, offer a benefit and should be realized. Yet due to the approach chosen and the overall objective, the flows on the resulting grid were analyzed on an equivalent zonal model and not on a full nodal model. The objective of Task 2.4 is therefore to perform sanity checks to assess the ability of these structures to be implemented and operated in the existing 220-/ 380kV transmission system. For this purpose the existing grid in 2030 is taken and the new grid reinforcements – defined by task 2.3 in the different strategies per scenario – are implemented in it. In a second step the load and demand scenarios are adopted to be in line with the assumed situation in 2050. Two special cases, the “summer-low” situation and the “winter-peak” situation, are taken as representative cases and the grid utilization is analyzed for the continental transmission system (former UCTE-Grid[1]). Based on the results, critical branches are detected. In a third step, for these branches in the grid, counter measures are suggested, that eliminate the detected constraints and allow a secure operation of the transmission system. Finally, an economic assessment reveals the expected costs to invest in counter measures and compares them to the costs for the initial inter-cluster structure of the analyzed scenario. So afterwards it can be assessed whether the inter-cluster structures and their implementations in the system are economical beneficial.

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[1] Union for the Co-ordination of Transmission of Electricity: The grid represents all countries of continental Europe whose electrical grids are connected synchronous. Not represented countries are Ireland, United-Kingdom, Norway, Sweden, Finland, Estonia, Lithuania and Latvia. Only the continental system of Denmark is included.

2. Approach for grid operation ability assessment

The question to be answered after the grid development in task 2.3 is whether the defined architectures, and the technology solutions to realize them are able to cope with the flows expected at 2050 without overloads. For this purpose it is planned to include these new elements in the 2030 system and assess the load-flows on the single lines. If problems occur counter measures can be implemented that reduce the utilization of constraint components thus allowing an operation within save parameters.

The whole European transmission system consists out of more than 10.000 nodes. Given the complexity of the grid analyses process and the long time horizon it seems unfeasible to analyze the whole system. Yet problems that occur in particular areas across Europe are comparable and counter measures that solve operational constraints in a given area will also solve similar constraints in another area. Therefore, to reduce the effort of the task, critical branches are detected and counter measures are checked for the effectivity for these branches. After this "*proof of concept*" these counter measures are also applied for the other critical branches in the architectures and in the different load-flow situations. Figure 1 shows the workflow to receive results and proves the sanity of the architectures at stake.

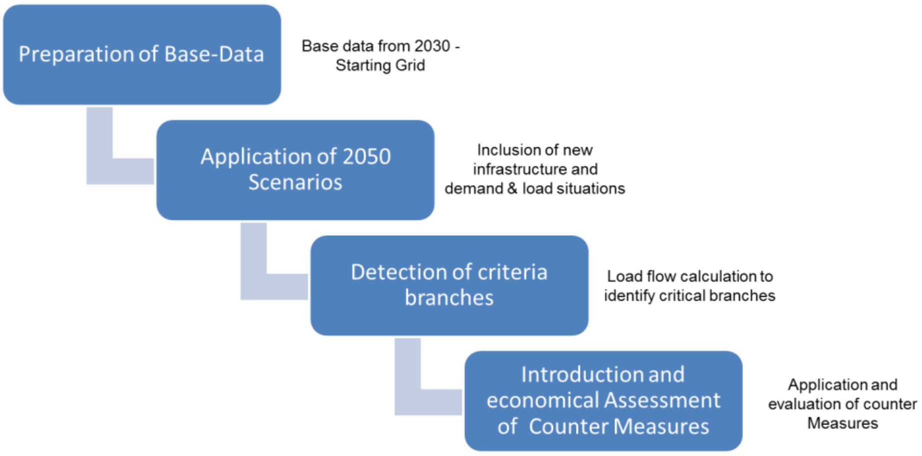

Figure 1: Overview Approach in Task 2.4

The work starts with the preparation of the base case load flow data. For this a data set is used, that has been the outcome of the TYNDP-process within ENTSO-e. It represents the most likely situation the European transmission system will be in, in the year 2030. This data set has to been processed and implemented in the grid analyses tool PSS$^{©}$E, which is the platform of analyses in Task 2.4.
(See Chapter 3.3)

Once the starting situation in the base case has been prepared the analyses of the scenarios are started. For this, the infeed and load situation of the electrical nodes, in the different clusters, has to be adjusted to meet the final generation situation in the different scenarios. In addition the new grid reinforcements, which are part of the strategies, to reach the target architecture will be implemented and connected to the electrical nodes of the starting grid. Having all of this prepared load flow analyses are run to determine the utilization of the lines in the continental transmission system. (See Chapter 3.4)

As mentioned the analyses of all constraints in the European transmission system is an exhausting, time-consuming process. Within ENTSO-e this tasked is split among the TSO-community, where every TSO focuses on its transmission system. Since the project must look at whole Europe, but resources are not sufficient to analyze all parts of the transmission system, attention is focused on critical branches. These branches are characterized by significant constraints and are therefore critical for operation. The selection is based on criteria that represent the overall status of all electrical elements (lines and transformer).
(See chapter 2.1.2)

Finally for these critical branches, counter measures are introduced in order to free the system of constraints. A variety of counter measurements available in grid development planning is described and assessed in relation to their applicability for the analyses in task 2.4. For the selected counter measures a "*proof of concept*" is made to proof their effectiveness in the given planning environment. The measures can also be prioritized in sense of their costs and effect of the target structure from task 2.3. Such measurements are preferred that affect the given target structure least and have lowest costs. These analyses are done to eliminate all critical branches and have a final situation that allows safe operation. The assessment ends with a short economical evaluation of the needed cluster-internal investments that are to be seen as "On-Top" investments on the previously defined reinforcements of Task 2.3.
(See Chapter 4.3.3)

2.1. Analyses Situations and Assessment Criteria for grid utilization

The grid analyses tasks opens a very vast field of different focuses and levels of detail that can be looked at. Due to the complexity and the dynamic of the electricity transmission system analyses usually require very detailed information about grid components and market conditions (infeed and load). The further one looks into the future the less accurate this information becomes. In the case of task 2.4 the scope of analyses is 35 years ahead, what limits available information and its accuracy. Therefore the scope of analyses was reduced in task 2.4 to aspects which can be analysed with the available data and to limit the workload to a feasible extent. The following description shows the dimensions that have been used to focus the work.

2.1.1. Selection of Scope of Analyses

Selection of geographical Scope – Selection of Area for Analyses

The European energy system contains 5 interconnected systems, yet they are not connected synchronously:

- Irish transmission system (Ireland & Northern-Ireland)
- Great Britain transmission System (without Northern-Ireland)

- Nordel-Region (Norway, Sweden, Finland & Denmark East[2])
- Baltic System (Estonia, Latvia & Lithuania)
- Continental Europe (former UCTE-System)

The UCTE System contains all countries in continental Europe and is by far the biggest. In Task 2.4 the analyses are concentrated on this system. The availability of accurate grid data is a challenging point and the results of analyses vary strongly with minor differences in the information. For the analyses performed in task 2.4 accurate grid data was available for the former UCTE region, which is why the analyses were limited to this area.

Timely focus of Analyses – Selection of *Snapshots* for Analyses

In today’s grid planning tasks the usual approach bases on the calculation of 8760 use cases for the analyzes – one for each hour of the year. The automatic calculations used for grid analyses on shorter time horizons (usually +10 years or +20years) allows the simulation of all timestamps and afterwards a selection of the most critical use cases for grid utilization. These different situations usually very in details like exact power plants online and the current load situation in different grid nodes. In long term grid development approach (+35 years in this situation) in e-highway 2050 this effort is not required for two main reasons. On the one hand, there is the problem of accuracy of allocating power generation and demand to the single grid nodes. For 2050 this allocation of power generation and demand is done by an application of algorithms and abstracting from exact knowledge (Chapter – preparation of data). Subject of aggregation and similarity of uses cases, which excludes attributing power generation and demand to the exact grid nodes leads to an aggregation-effect and as a consequence, use-cases that are similar to each other. As in task 2.4 the “big-picture” in Europe is envisaged, the single use case, which are interesting only for local constraint, are not in the subject matter scope.

Therefore analyses in task 2.4 focused on the two most critical situations for the transmission system:

- **Summer Low (SL)**
  The summer low is characterized by a high infeed of renewable energy sources and thus a low remaining electrical consumption in Europe – to be satisfied by conventional generation. Since production from RES is often higher than demand in these situation the summer low defined moment of highest spilled-energy (dump-energy).
- **Winter Peak (WP)**
  The winter peak is characterized by a very high load and thus a high production in the system. The situation is critical for energy supply (highest ENS value – if existent) and a high utilization of grid components.

This approach led to the selection of the following hours in the different energy-scenarios:

Scenario	Winter Peak	Summer Low

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[2] The transmission grid of Denmark West is also connected to the UCTE-system.

X-5	Nov. 27th – 6 pm	Jun. 23rd – 2 pm
X-7	Jan. 9th – 6 pm	Jun. 23rd – 1 pm
X-10	Nov. 26th – 6 pm	Jun. 24th – 1 pm
X-13	Nov. 27th – 6 pm	Jun. 6th – 2 am
X-16	Nov. 27th – 6 pm	Jun. 23rd – 1 pm

Table 1: Selection of Snapshots per Scenario

Strategies for Grid Architectures – Selection of Architectures for Analyses

In Task 2.3 three different strategies have been pursued for the grid architecture definitions. Following the defined transmission requirements the available technologies have been chosen based on different assumptions towards the public acceptance of new transmission infrastructure. Assuming a positive attitude (strategy 1), new overhead-lines (OHLs) were deemed possible. Assuming a negative attitude in the population (strategy 3), the only possibility to reinforce the system are new cable systems.[3] And finally, assuming a neutral attitude (strategy 2), a re-use of existing corridors is possible. The latter one explicitly includes the possibility to build new OHLs parallel to already existing ones. The main difference between strategies 1 and 2 being the possibility to deploy new transmission corridors, where there are no corridors yet developed in 2030.

If the possibility exists to build OHLs they are preferred over cables due to cost considerations. In this situation usually also AC-system are preferable, since they don't require expensive converter stations. This leads to the result, that the final grid elements introduced in strategies 1 and 2 are very similar. On contrary strategy 3 demands cables for new transmission lines. Since distances between the selected clusters are often 100km and longer, DC connections are the only feasible options. Finally it has been decided to focus on the strategy 3 (as a DC architecture) and strategy 2 (as an AC variant). Strategy 3 is dominated by DC reinforcements ant therefore holds a new challenge for grid operation. Strategy 2 has been preferred over 1 since the realization of these structures deemed more realistic and thus results are more important for actual grid planning.

Scenarios to be analyses - Selection of Scenarios for Analyses

In e-Highways previous steps five very different energy scenarios have been defined to assess the need for grid architecture in 2050. They can be put into comparison with today's energy supply system. Scenarios X-10 (Big & Market) and X-13 (Nuclear & Large Scale fossil fuel with CCS) are relatively close to what the energy system looks like today and is expected to look like in 2030 vision of the TYNDP. Large power plants do exist which are close to the demand centers and can provide power locally – either for voltage stability or for local demand supply. Scenario X-16 (Small Scale & local) forecasts an evolution to a decentralized organization of the energy supply. The transmission grid is required to supply demand in high load periods which are also accompanied by periods of low production from renewables. So the transmission system still fulfills its originally task, which it has been designed for – only in less hours of the year. X-5 (Large scale RES) and X-7 (100% RES) are extreme

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[3] Also the refurbishment of existing Overhead-Lines is possible to a particular amount. But only where OHLs are already in place in 2030.

scenarios, extremely different to the situation today. As a result, their study was difficult and no convergence of the load flow could be found. It does not mean that these scenarios are not feasible but that additional efforts would be necessary to simulate them. Due to the huge work necessary, it was not possible within this task to do it before the project's end. However, it highlights the need for more advanced methodologies to study so different network configurations. The WP8 of the project has worked in parallel on these issues and developed an innovative algorithm to tackle these problems by automatically adapting the reactive power compensations. It could be applied in future studies.

The undertaken attempt consisted of the following steps, each step being theoretically easier since more aspects of the power flow are disregarded in comparison to the previous run:

1. run an AC load flow calculation considering reactive power limits
2. run an AC load flow partially discarding the reactive power limits
3. run an AC load flow after modifying the tap positions of transformers and the voltage set points of generators
4. run an AC load flow fully discarding reactive power limits
5. run a DC load flow

The focus of analyses in Task 2.4 is therefore set to scenarios X-10, X-13 and X-16.

Note:
It is not said, that Scenarios X-5 and X-7 are not feasible for transmission systems. The implementation of such amounts of renewable production is technically feasible, but it requires new planning standards and concepts in grid development.

Based on these considerations the grid analyses concentrates for the grid of continental Europe (UCTE) on three scenarios, two strategies for grid architecture development and on two snapshots per strategy - Winter Peak & Summer Low. Figure 2 visualizes the 12 calculated cases:

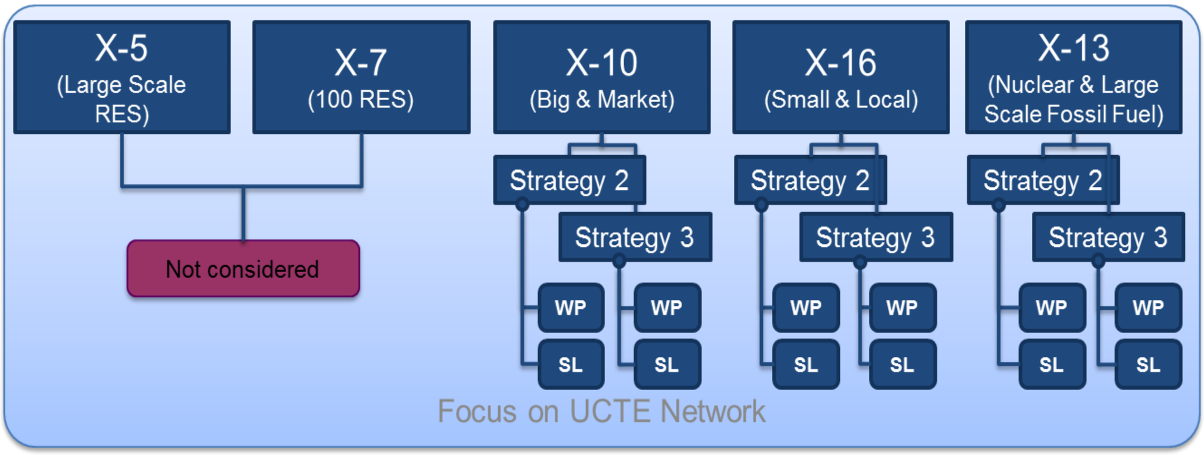


Figure 2: Case Selection for Grid Analyses in 2.4

2.1.2. Assessment Indicators for grid utilization

The grid analyses itself can be done in very different ways depending on the objective of the assessment. In general one can distinguish between dynamic and static grid analyses. Latter are in focus of task 2.4, while dynamic analyses are subject of working package 4 of the study e-Highway 2050. The field of static grid analyses contains thermal line utilizations and voltage stability problems.

In static grid analyses the focus is given on processes that appear or change on hourly basis. These are mainly the utilization of grid elements (lines and transformers), the losses on the elements and their voltage level. What also interests is the required amount of reactive power that needs to be provided to the system to assure a constant voltage level. Later requires combined power/ reactive-power load flow calculations.

Load-Flow Analyses performed in Task 2.4

In Task 2.4 the analyses is built on the UCTE system that represents the transmission system of continental Europe. For the analyses, which were performed by TSOs, access to ENTSO-e data was granted. This data is highly confidential and can only be used by the TSOs of ENTSO-e themselves. In this data set a complete status of the European transmission grid (220kV/ 380kV) is given, extended by relevant elements in lower voltage that also support the transmission task. What is not given in this data set is information about the geographical position of the elements. In Task 2.2 of the project it has been determined which element is in which cluster of the cluster model, but the exact location within the cluster is not available. This increased the complexity of counter measures implementation into the system.

For task 2.4 no major voltage or reactive power problems were detected and therefore the focus was laid on the utilization of lines, which is caused by power flows in the different situations. To assess the severity of the grid utilization two indicators are looked at.

Line utilization (U): The line utilization is a value describing the ratio in % between actually transported power and rated power of the line. The transported power is the sum of active and reactive power transported. This value can be calculated for all elements *e* in a cluster *cl*.

$$U_{e,cl} = \frac{\sqrt[2]{P_{e,CL} + Q_{e,CL}}}{S_{e,cl}}$$

Where:
e = Element
cl = Cluster
P = Active Power
Q = Reactive Power
S = Rated Power

Not transmittable Power (NTP): The not transmittable power is an additional indicator to assess the severity of the constraints inside each cluster by weighting them with the rated power (e.g. a 1.000MVA line over-utilized by 20% (120%) is more critical, than a 500 MVA line over-utilized by 30% (130%)).

$$NTP_{e,cl} = S_{e,cl} * (U_{e,cl} - 100\%), \qquad when\ U_{e,cl} > 100\%$$

Where:
e = Element
cl = Cluster
U = Utilization
S = Rated Power

This indicator holds the advantage that it also considers the capacity of the constrained elements. Looking only at the utilization would mean that elements with a low rated power have the same weight as elements with a high rated power. This would mean that for instance several "small" constraint elements in a cluster seem more critical than one "big" constraint element in another cluster. The NTP-indicator helps to focus on the most important problems (table 2 holds an example)

Cluster	Element	Rated Power	Utilization	NTP	Sum
A	1	400 MW	**130%**	120 MW	240 MW
A	2	650 MW	**80%**	0 MW	
A	3	800 MW	**115%**	120 MW	
B	1	2.000 MW	110%	200 MW	**275 MW**
B	2	1.500 MW	105%	75 MW	

Here it can be seen, that a concentration on the utilization itself would lead to the conclusion, that Cluster A is the critical one. While considering also the rated power of the elements Cluster B is more critical.

Given these two indicators it is possible to provide key-values for each cluster which classify the severity of constraints in them.

As mentioned above for Task 2.4 clusters are incremental elements for analyses. Since a cluster contains a variety of elements (lines and transformers) an average of the indicator "utilization" must be made as representative for the whole cluster. Elements which are utilized by less than 100% are not considered since there is no operational problem for them.

Utilization in N and N-1 situation

In grid analyses there are two main situations that are considered when the reliability and stability of a grid needs to be assessed.

- **N-0 case:** In this case all elements of the inter-cluster System, detected in task 2.3, and the starting grid are in operation
- **N-1 case:** In this case 1 out of the system is malfunctioning, thus increasing the utilization of the other elements. It is state of the art in grid planning standards that an N-1 situation must be manageable for the transmission system.

The starting grid is taken from the TYNDP 2014 as the final grid for the time horizon 2030. Since the ENTSO-e planning standards have been assumed the starting grid was considered as N-1 secure. Therefore in the following analyses the default of elements in the starting grid has not been considered for N-1 cases. Only elements of the new structures and a consequence of their default on the starting grid were analyzed in N-1 contingencies. It has been tested in the TYNDP already whether the default or intra-cluster elements lead to N-1 violations of elements in the starting grid.

As mentioned above for analyses in Task 2.4 only single clusters are selected. Since a cluster contains a variety of elements (lines and transformers) an average of the indicator “utilization” must be made as representative for the whole cluster. Elements which are utilized by less than 100% are not considered since there is no operational problem for them.

Δ30%-Utilization-Approach

The input data of the grid utilization assessment are constituted by the full AC load flow calculations results described below. The variable used for checking the viability of the operation is given by:

$$\Delta loading = maximum\left(loading\ (N-1)\right) - loading(N)$$

that is calculated for each branch, where:

- Maximum loading (N – 1): maximum loading provoked by an outage of a reinforcement in the n – 1 analysis
- Loading (N): loading of the base case
- Loading: quotient of the current of the branch by the maximal current of the branch $(\frac{I}{I_{max}})$

The criterion for assessing critical branches is given by

$$\Delta loading > 30\%$$

The 30% threshold is justified by the fact that, in the N situation of the base case, a strongly loaded branch is loaded at 70% at the most. Therefore adding 30% loading to 70% would guarantee that loading $(N-1)_{max}$ = 100% and therefore a secure operation. On the other hand, if Δ-loading is higher than 30%, the loading would supersede 100%, which indicates a potentially insecure operation and the need for counter measures.

Example from used base data: In winter snapshot case (21st January, 10h30 CET) created by ENTSO-E), out of the 14310 branches,

- for 242 branches (1.7% of all branches), loading > 70%
- for 14068 branches (98.3% of all branches), loading ≤ 70%

This example shows that the loading of (almost all) branches is smaller or equal to 70%, and accepting a 30% increase of the loading due to the outage of a reinforcement will bring the loading to 100%. This then guarantees security of operation.

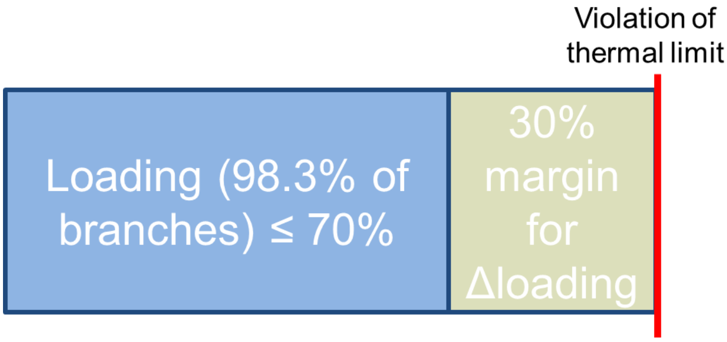


Figure 3: Δ30%-criterion - Statistical Line loadings in base case

Remark: This differential consideration enables to mitigate the influence of the choice of timestamps and to identify the effect of the reinforcements onto the existing grid (TYNDP 2014 grid, time horizon 2030).

2.1.3. Counter Measures and Evaluation context of Task 2.4 analyses

Once the critical lines in the European clusters are detected, the objective of analyses in task 2.4 is to identify counter measures that will solve these constraints to enable a reliable and secure grid operation. The idea is that counter measures should not affect the included reinforcements from the grid development task, but only the existing grid. The following list of counter measures does exist in grid development planning:

- reactive power compensation
- cluster-internal change of the connection point of reinforcements
- split of DC reinforcements
- change of voltage level (to a higher voltage level)
- change of technology (AC ⇔ DC)
- change in transmission medium (cable vs. overhead lines)
- introduction of local reinforcements

This list is not thoroughly, but it covers the main methods in grid planning. Not all of these counter measures can be applied for very long time planning, as given in task 2.4. Nor is it possible to consider all in the context of the available grid data. The following explanations give an overview about the main points as assessed for application in the analyses.

Reactive power compensation
In this project it was not dealt with overloads due to a too strong active power requirement. Moreover, during the calculations, effects like voltage collapses that could indicate the need for reactive power compensation played a minor role in the analyzed scenarios.

Change of connection node (Cluster- internal)
As described in chapter 3.2., for each cluster main switching stations are defined by detecting strongly connected/ highly meshed nodes. Seen from today, they are the most feasible connection point for bulk power transmission lines. In the analyses there was little potential for

defining new viable nodes for connecting the reinforcements. Yet in more detailed grid planning for shorter time horizons other nodes may be more suited for these connection points.

Split of new transmission corridor

The idea behind this method is to split transmission lines from one cluster to another and relieve the pressure set to single grid nodes. For an application of this option one needs detailed knowledge about the geographical location of nodes and their connection to other nodes – both not available for analyses here. But basically the method leads to the same results as the local reinforcements in existing technology as it will be shown below.

Change of voltage level (to a higher voltage level)

This possibility may help to reduce reactive power issues in the system and improves system resistance. It is an option only for new grid elements, since most lines are operated at the highest usual AC voltage level in Continental Europe (380 kV) already.

Change of technology (AC ⇔ DC)

If an AC line is overloaded, the transformation to a DC line would limit the active power on the branch itself, but it might lead to new overloads on branches of the AC transmission grid in the neighborhood. Therefore the benefit of this method seems limited.

Switch in transmission medium (cable vs. overhead lines)

Usually, cables are replaced by overhead lines in order to increase the transmission capacity of the branch. As, however, very few lines are cables, the potential of this method is limited in our case. Also this possibility only exists for DC reinforcements, since transmission distances are too long to be realized in AC cables.

Local reinforcements

This method is constituted by the introduction of parallel branches (380 kV lines, 220 kV lines and transformers) to the critical branch. It is very relevant for the analyses described in this report as can be seen in the next paragraph.

In the work of task 2.4 not all of these counter measures can be considered and assessed. Due to the above mentioned points the focus was laid on the introduction of local reinforcements that assure improve security. Neither was it possible to include these local reinforcements in all analyzed clusters manually. Therefore a “proof of concept” was made to show, that this method does release the grid from all constraints when simply applying this measurement. It allows receiving a secure grid, but can lead to more grid reinforcements and therefore higher additional costs than a more sophisticated application of counter measures. Yet, as will be shown later, the additional costs for local compensation are negligible in contrast to the costs for the inter-cluster grid architectures.

Assessment of the efficiency of implemented CM (“Proof of Concept”)

For the analyses here two counter measures are considered as feasible to be tested. On the one hand the introduction of new intra-cluster/ local reinforcements and on the other the “split” of new links (without change of grid nodes). Latter measure leads to a reduction of lost power in case of a contingency event and thus relieves the remaining grid elements. It can be shown, that both lead to comparable results. This, in its turn, justifies the use of one – in this case local reinforcements – for further analyses.

For scenario X16 summer low strategy 3, the values for maximum (loading (N – 1)) – loading (N) are observed in the entire Continental European grid (the tripped element is a DC link with current flow of 1459 MW).

> <u>Without corrective measures for 6 elements</u>:
> *maximum (loading (N – 1)) – loading (N)* > 30%.
>
> <u>Option 1: Split of DC reinforcements:</u>
> If the DC-link is splits into two parallel HVDC-links, i.e. if the original 1459 MW on the DC link is split into two times 729 MW per link, there is no element with *maximum (loading (N – 1)) – loading (N)* > 30%. The highest such difference *= 23%.*
>
> <u>Option 2: Local reinforcements in existing technology:</u>
> The HVDC is again at its full active power (1459 MW), and parallel elements are introduced into the TYNDP 2014 grid (time horizon: 2030) according to the following rules:
>
> 1. For all circuits of the transmission grid (U (both terminals) >= 220 kV) where maximum (loading (N – 1)) – loading (N) > 30%, one parallel circuit is introduced
> 2. For all circuits of the transmission grid (U (both terminals) >= 220 kV) where maximum (loading (N – 1)) – loading (N) > 60%, two parallel circuits are introduced
> 3. If two or more such circuits are parallel and if maximum (loading (N – 1)) – loading (N) > 30%, one parallel circuit is introduced
>
> There is no element with maximum (loading (N – 1)) – loading (N) > 30%. The highest such difference is 29%.

This shows that assessing the local reinforcements in existing technology is equivalent to assessing the split of DC reinforcements, in terms of the gained grid security improvement. Costs are somewhat different since a “split” of a DC link leads to different costs than an additional transmission line. The cheaper solution is case-dependent and not considerable here. Therefore focus is given to local reinforcements, since their costs can be determined with the information available in the analyses.

3. Base data and results for Analyses in Grid Contingency Analyses

The task of grid analyses is a very complex subject that requires a high accuracy of data, both from generation & demand information and from technical parameters of the transmission system and its elements. Naturally with increasing temporal distance to the point of interest this accuracy is decreasing due to the high uncertainties. In fact it is unknown where exactly lines are built in 2050 or where a power plant is connected to the grid. Therefore assumptions have to be made to reduce the complexity of the problem and allow a reasonable estimation of the situation in 2050.

In this chapter it is described which basis has been used for the analyses and how the input data – grid architectures and generation & demand profiles – has been processed to reach a working grid model.

3.1. Preparation of the available grid model

The transformation between the CIM/XML and raw-format causes the loss of the following information, the effects of which will be described in the following chapters:

- RDF ID keys (unique identification key in the CIM/XML format)
- Generation types (nuclear, hydro, solar, thermal, etc.)

Furthermore, the available case is a winter case - the lines capacities therefore tend to be too high for the summer period. The used grid model (TYNDP 2014 (time horizon 2030) grid model in raw format) does not comprise the British, Irish, Nordic and Baltic grids. In general, the tap of phase shifters was left unchanged. Furthermore, the eliminated grid is represented by equivalent loads corresponding to the flow to the eliminated grid. The following preparation was necessary in view of Task 2.4 aims to adapt the model for its requirements:

- Removal of lower voltage grids
- Removal of East Denmark (i.e. Zealand)
- Attribution of the nodes to the clusters
- Definition of main switching stations (when necessary)
- Treatment of existing DC links
- Modification of some voltage set points and reactive power limits

Removal of lower voltage grids

1. In the available load flow model, the lower voltage levels are not modelled consistently: some countries provided more details than others.
2. The inclusion of lower voltage models tends to increase the size of the dataset a lot.
3. Lower voltage models often have large impedances that render their presence in the model dispensable.
   Therefore,
   - The grid parts where U < 220 kV were removed except in Greece, the Netherlands and West Denmark where those levels have a transmission function.
   - An equivalent load was created at the interface between the remaining model and the removed model, in which the active and reactive power values were set equal to those on the interface. In other words, the eliminated grid is represented by equivalent loads corresponding to the flow to the eliminated grid.

Removal of East Denmark

East Denmark (Zealand) is synchronously connected to the Scandinavian Grid and not to the Continental European grid; therefore it was removed from the model.

Attribution of the nodes to the clusters

In the e-Highway 2050 project, many countries include several clusters. For the TYNDP 2014 grid (horizon: 2030), given in the CIM/XML format, a list indicates the nodes' clusters by means of the RDF ID key. However, as the RDF ID key is not present in the raw model we used, the clusters of nodes of multi-clusters countries had to be found out.

Definition of main switching stations (when necessary)

The main switching stations are the nodes where reinforcements (AC or DC) determined by Task 2.3 are to be connected. For many clusters, the main switching stations are already defined. When this wasn't the case, the main switching stations (preferably strongly connected nodes) were chosen.

Treatment of existing DC links

In the starting grid (TYNDP 2014, time horizon 2030), some clusters are connected by DC links. In our model (only Continental Europe) this means

- on the one hand DC links connecting Continental Europe clusters (both terminals had to be identified):
- On the other hand DC links connecting Continental Europe clusters to overseas (only the Continental Europe terminal had to be identified) :

The complete list of DC links is given in annex A.

Case where the DC links connect different countries:

In that case, the NAME part of the Bus Data starts with an X (<= X nodes system).

Example: French side of the DC link between DC04ES and DC14FR. In the bus data, the following entry is found:

```
78682,'XGA_CU1F    ', 320.0000,1,     0.000,     0.000,  99,  99,1.09063,  -1.1459,9999
```

The X node indicates it's a (DC) tie-line. CU corresponds to Cubnezais in France (and GA to Gatica in Spain).

Case where the DC links are within a country

This only concerns Germany. The implementation has been done in close cooperation with the German member of former ENTSO-E Working Group *Network Models and Data*. In the table below, the left column shows the DC links that had to be identified in the model, and the central and right column show the indications provided the German member of former ENTSO-E Working Group *Network Models and Data*.

DC Link	Terminal 1	Terminal 2
dc28_be - dc33_de	HGUE Lixhe D74-BE	HGUE Oberzier D74-BE
dc31_de - dc33_de	HGUE EMDB	OSTRAT
dc31_de - dc35_de	WEHRND	URBER
dc31_de - dc36_de	HGUE EMDB	HGUE PHILI
dc31_de - dc37_de	HGUE BRUN	HGUE GROGH
dc33_de - dc36_de	OSTRAT	HGUE PHILI
dc34_de - dc37_de	LAU	MEITGN
112_ns - 31_de	DolWin 1	HGUE BRUN

Table 2*: DC link to be identified, Terminal 1 and Terminal 2*

Then, a list was constituted with the nodes whose NAME part of the data contains ‘HGUE’ (German: Hochspannungs-Gleichstrom-Übertragung) and their corresponding clusters. Collating this list with the table above, some DC link terminals could be identified. The DC links that couldn’t be found were created between strong nodes of the clusters they connect.

Modification of some voltage set points and reactive power limits

Vis-à-vis the base case, the calculated cases show very different flows, which in their turn sometimes render a modification of the voltage set points, the reactive power limits and the transformer tap positions necessary.[4]

3.2. Used outputs from System Simulations analysis and overlay-grid development

3.2.1. Results from ANTARES

The results from ANTARES corresponding to the analyzed cases (see 3.1.) were obtained for the aforementioned scenarios by year and hours (the ANTARES results do not depend on the strategy). Data was directly compiled from the results of Task 2.3 (as can be found in D2.3). One excel file per studied scenario and timestamp was created, containing on the one hand the load and generation values for each cluster (*energy_mix*) and on the other hand the flows between clusters used for the flows on DC links (*links*).

---

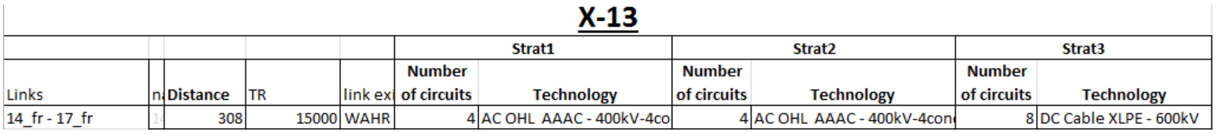
[4] Remarks: In general, the tap of phase shifters was left unchanged. Also PQ-nodes were never transformed into PV nodes.

3.2.2. Technology matrix

To implement the transmission requirements from task 2.3 (each described by a length and a capacity) in the grid model, a technology-matrix was used. The technology matrix aims at summarizing the results gained in WP3 of the e-Highway2050 project. The part of the matrix that was used in Task 2.4 gives the specific parameters of AC lines and transformers. Depending on the chosen strategy different technologies with different technical parameters have been extracted. But given the matrix it was known that all solutions are feasible for the defined transmission requirement.

3.2.3. Transmission requirements matrix

The information is contained in an XL file whereas there is one sheet per scenario. Below one can see the transmission requirement for scenario X-13 and for link 14_fr – 17_fr, where a 15 GW request is 'translated' into (Strategy 1) into 4 Strategy 1: 4 400 kV AC Overhead Lines, (Strategy 2) into 4 400 kV AC Overhead Lines and (Strategy 3) into 8 600 kV DC Cables.



X-13

					Strat1		Strat2		Strat3	
Links	n	Distance	TR	link ex	Number of circuits	Technology	Number of circuits	Technology	Number of circuits	Technology
14_fr - 17_fr	1	308	15000	WAHR	4	AC OHL AAAC - 400kV-4co	4	AC OHL AAAC - 400kV-4con	8	DC Cable XLPE - 600kV

Figure 4*: example of transmission requirement matrix use*

15 extra GW are needed between both clusters (distance between the centers = 308 km). That extra need can be covered by

- Strategy 1: 4 400 kV AC Overhead Lines
- Strategy 2: 4 400 kV AC Overhead Lines
- Strategy 3: 8 600 kV DC Cables

This information is used for Strategies 2 and 3 and for AC Overhead Lines, cables, converters and transformers:

- Multiplying the distance (308 km) by the specific parameters of the line, one obtains the parameters of the 4 overhead lines.
- The overhead lines usually connect main switching stations of both clusters. However, if the voltage of a main switching station is not the same as the voltage of the additional AC line it is connected to, a transformer, the parameters of which are included in the Technology matrix, is added.
- As DC links are modelled by pairs of injections and loads, it is not necessary to model the AC/DC converter and the DC cable.

3.3. Creation of the load flow datasets

3.3.1. Creation of the basis dataset

Principles

For each studied case the sum of all balances of the Continental Europe clusters and the flows on DC links connecting Continental Europe to other Synchronous Grids (Scandinavia, Baltic Countries, Great Britain, Ireland, North Sea and North Africa) should equal zero.

As some DC links to other synchronous grids are not part of the starting grid but part of the reinforcements, the basis dataset might be unbalanced; in that case the mismatch is located in the slack node (in a load flow grid model, the slack node compensates difference between the power injections (generation, imports from non-modelled grid models) and power consumptions (loads, exports to non-modelled grid models, losses)).

Scaling load and generation according to the results from Antares

The table below shows the output (active power [MW]) of ANTARES for Scenario X-13, Average Year, Summer Low, cluster 02_ES. It can be noticed that the generation types are given in detail (e.g. solar, biomass, nuclear).

Areas	02_ES
TOTAL	4478
LOAD	5454
H. ROR	700
WIND	720
SOLAR	2093
BIOMASS	376
NUCLEAR	0
GAS	574
COAL	0
LIGNITE	0
H. STOR	15
UNSP. ENRG	0
SPIL. ENRG	0
LOLD	0
OV. COST	33940
BALANCE	-976
PSP GEN	0
PSP PUMP	0
generation	4478
balance	-976

Table 3: *Output from ANTARES for Scenario X-13 with the target active power for each generation type and for the load is given*

The goal of scaling is to implement that ANTARES output given for the cluster model (i.e. a **zonal** model) into the detailed **nodal** grid model we use.

- All loads of cluster 02_ES were scaled proportionally to the target load (5454 MW).
- All generations of cluster 02_ES were scaled proportionally to the target generation (4478 MW).
- The target generation is the sum of TOTAL (total generation) + UNSP.ENRG (unsupplied energy) + SPIL.ENRG (spilt energy) + PSP GEN (generation of pump storage devices) + PSP PUMP (pumping of pump storage devices). This method corresponds to the indication obtained from task 2.3. For all cases studied the sum of the balances was calculated. Those balances

are the difference between the cluster's generation (calculated according to the described method) and the cluster's load. The sum is the balance of the Continental Europe clusters and of the flows connecting Continental Europe to other grids.

- There was no independent scaling of each generation type (e.g. solar => 2093 MW, biomass => 376 MW, nuclear => 0 MW) because
    - The used raw model does not contain the information about the generation type that is given in the CIM/XML model.
    - The location of the generation is not known for 2050 thus this is the best estimation available.

As illustrated in the example above, the scaling rules are

- All loads of cluster are scaled proportionally to the target load provided by ANTARES.
- All generations of cluster are scaled proportionally to the target generation. (The target generation is the sum of TOTAL (total generation) + UNSP.ENRG (unsupplied energy) + SPIL.ENRG (spilt energy) + PSP GEN (generation of pump storage devices) + PSP PUMP (pumping of pump storage devices) <= ANTARES). Therefore there is no independent scaling of each generation type (e.g. solar, biomass, nuclear).

The following table shows the target total load, total generation and total import from other synchronous grids (the total load and the total generation of the basis grid = 370 GW).

	Total load [GW]	**Total generation [GW]**	**Total import from other synchronous grids [GW]**
X-5 Winter Peak	580	449	130
X-5 Summer Low	427	331	96
X-7 Winter Peak	510	412	98
X-7 Summer Low	413	401	12
X-10 Winter Peak	481	414	67
X-10 Summer Low	370	329	41
X-13 Winter Peak	524	479	45
X-13 Summer Low	415	378	36
X-16 Winter Peak	338	306	31
X-16 Summer Low	297	299	-2

Table 4: T*otal load, total generation and total import from other synchronous grids*

That table illustrates the challenge of the scaling. Indeed, the sequence of the scaled clusters had to be chosen carefully; in order to constantly ensure the load flow convergence, it is important that the slack node never absorbs or consumes a too large active power. Indeed, if the slack node's balance is higher than ca. 10’000 MW or lower than ca. -10’000 MW, the voltage in the vicinity of the slack node collapses and the load flow can no longer be calculated.

Flows on DC links

The loads on the existing DC links internal to Continental Europe and connecting Continental Europe to other grids are set to *min (starting_grid_GTC; Flow given by generation dispatching)*

Therefore, the existing DC links are ‘filled up’ before using the new ones, provided by the DC reinforcements, are starting to be used. The motivation for this was not to put too much constraint on the vicinity of the AC/DC converters of the DC reinforcements.

E.g. Scenario X-13, Summer Low

- Flow (DC14_FR => DC04_ES) = 20 MW
- GTC (DC14_FR – DC04_ES) = 1000 MW
- Min (GTC; Flow) = Min (1000 MW; 20 MW) = 20 MW
    - Load on the French side set to 20 MW
    - Load on the Spanish side set to -20 MW

These flows are obtained from the XL files described in 3.3.1.

3.3.2. Creation of the reinforcements dataset

The reinforcement-dataset is an add-on load flow dataset that includes the reinforcements coming from task 2.3.

For each studied case, the reinforcements between clusters corresponding to Strategy 2 and Strategy 3 are turned into reinforcements dataset connected to the main switching stations.

AC reinforcements

If the reinforcements is constituted by AC elements, line(s) with the specific electric parameters yielded by the technology multiplied by the distance between the clusters are created, and if necessary transformers complete the additional infrastructure (cf. 3.3.3.)

DC reinforcements

If the reinforcements are constituted by DC elements, the DC line is represented by pair(s) of positive and negative injections.

- If a DC connection already exists between the clusters, the flow to be considered is *max (Flow given by ANTARES – starting_grid_GTC; 0)*
- If there is no DC connection between the clusters, the entire Flow given by ANTARES must be treated.

Therefore, the existing DC connections are ‘filled up’ before using the new ones, provided by the DC reinforcements, are starting to be used. The motivation for this was not to put too much constraint on the vicinity of the AC/DC converters of the DC reinforcements. These ANTARES flows are obtained from the XL files described in 3.3.1.

Reinforcements file

The aforementioned components (AC reinforcements and DC reinforcements) are put into a file in RAW format. Therefore there are 3 x 2 x 2 = 12 such files. The number is explained by the analyzed scenarios (3), the selected snapshots – Winter Peak and Summer Low – and the chosen strategies (2 and 3).

As ultimate step the complete dataset is created by merging the basis dataset with the reinforcement-dataset. There are therefore 12 complete datasets.

3.4. Grid analyses

3.4.1. Static Load Flow

With the help of a Python Macro, a full AC calculation of the (complete) load flow datasets is performed with PSS/E. Besides the active power, the AC load flow calculation enables to observe the reactive power and the voltage in the entire Continental European grid. No major voltage or reactive power problems were detected.

3.4.2. N-1 Load Flow

An n-1 analysis is performed, in which the n (AC or DC) reinforcements are subsequently tripped and each time a full load flow is calculated. The tripping of an AC-reinforcement appeared less critical than that of a DC-reinforcement. The two reasons for that are :

- AC lines are “passive” grid elements and the flow they are utilized with is a direct result of the physical parameters and the topology of the whole synchronous transmission grid. Therefore the flows “adapt” automatic to new conditions. On the contrary DC elements are controllable and an operation strategy can be defined for them. This means that flows in these elements do not adapt to new situations but remain within pre-set parameters. The operation strategy of these elements has therefore a high impact on their implementation in the existing system. In the current state this can lead to in-efficient operation causing more constraints. New operation strategies may improve this situation, but their development was not in focus on the analyses performed here.
- The capacity of unitary DC lines were supposed to be higher than those of AC. As a result, the tripping of a DC line had a higher impact on the parallel lines than the tripping of an AC line. It highlights the need for some limits on the maximal power transported by a single line to ensure N-1 safety (NB: this issue is independent of the AC or DC character of a line).

3.4.3. Compiled results of the load flow

In total, there were 12 (= 3 * 1 * 2 * 2) studied cases, because for X-5 and X-7 Summer Low & Winter Peak cases were not analyzed:

- Three analyzed scenarios (X-10, X-13 and X-16) **(3)**
- Average year **(1)**
- Hours **(2)** defined by
    - Winter Peak: Maximal Energy Not Served at the European level (Europe + North Africa + North Sea) in the start grid case
    - Summer Low: Maximal Spillage at the European level (Europe + North Africa + North Sea) in the copper plate case (& in the final grid case))
- Strategies 2 and 3 **(2)**

	X-10	**X-13**	**X-16**
Winter Peak	26 November 6 PM	27 November 6 PM	27 November 6 PM
Summer Low	24 June 1 PM	6 June 2 AM	23 June 1 PM

Table 5: Selected hours for each analyzed case for Winter Peak and Summer Low

For each studied case the results are compiled in an XL file containing

- One spreadsheet with the load flow results in the base case
- n spreadsheets with the load flow results with the tripping of a reinforcement

4. Results of Analyses

After the previous chapters introduced the approach chosen for task 2.4, the evaluation criteria and the data preparation, it is now shown which results the analyses have revealed for the existing transmission system. The main objectives of the following results are to assess:

- **Whether the existing system can be operated within the "state-of-the-art" security parameters?**
  The TSO-e community publishes grid codes that regulate the grid operation of the synchronous AC transmission system in continental Europe. These rules are taken as reference points to assess whether the grid is within save operation. It is not assessed or analyzed whether these codes are still applicable in 2050.

- **(if not) Where do constraints appear and how serious are they?**
  Based on the load flow analyses the most affected clusters are detected and the situation is visualized. The assessment is based on the indicators defined in 2.1.2.

- **Which reinforcements are required within the different areas?**
  In 2.1.3 counter measures have been introduced and evaluated towards their applicability for analyses in task 2.4. Based on this discussion two counter measures have been selected for further use and thus resolving grid constraints in the clusters.

- **How high are the additionally required costs for a save grid operation?**
  All introduced counter measures lead to additional investments, which then leads to an increased annual cost level of the final architecture. It is assessed how high these costs will be and what they mean for the overall benefit of the final architecture.

The results to be shown on the next paragraphs are focused on the analyses scenarios X-10, X-13 and X-16 the different strategies and the snapshots. Scenarios X-5 and X-7 are qualitatively discussed since there have not been any grid calculations made for them. See figure 5.

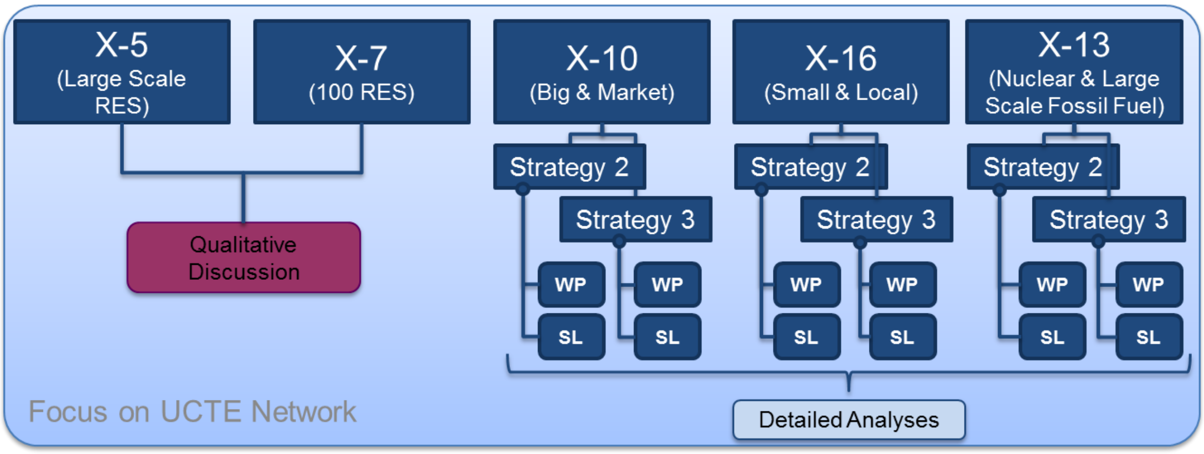


Figure 5: Presentation of Results – qualitatively and quantitatively

Therefore it is first focused on the qualitatively analyzed scenarios X-5 and X-7. It is explained what the challenges are to reach such an energy system in the EU and what are the consequences for the existing transmission system. Based on that recommendations are made for grid developers on how planning methodologies and standards might be adopted to prepare the transmission grid for the expected high utilizations.

Afterwards it is explained how the required amount of countermeasures has been assessed and how they have been included in the transmission system of the affected clusters. This is the basis for the different scenario analyses and the required amount of additional grid reinforcements.

Finally the three analyzed scenarios are introduced and analyzed. Based on the individual utilization in each of them, which is a direct result of the generation and demand localization, the critical clusters of the transmission grid are shown. They are then reinforced with local counter measurements which eliminate the critical cases and allow a save grid operation. The effects of the new elements for the line utilization have not been re-calculated. Instead it is assumed, that they will solve the constraints effectively, what has been shown in the “proof of concept”.

4.1. Qualitatively Analyses of Scenarios

In the scenario development process of working package 2 different extreme yet realistic scenarios for the European energy system have been developed. These scenarios, from which 5 have been selected for further analyses, do depict very different developments to reach the European climate targets in the year. The scenarios differ in absolute levels of installed generation capacities and load as well as in the localization of these capacities in relation to the demand centers in Europe. Latter remain, in terms of location, constant throughout all scenarios.

This leads to the effect that the scenarios affect the overall “transmission task” in Europe differently. A transmission task is defined by the relative distance between the production and the consumption of electric energy. Today’s energy system is characterized by a moderate transmission task. The installed generation capacities, of which a significant part is still conventional power plants, is located relatively close to the demand centers. As a direct result the existing transmission grid is designed to fulfill also a moderate transmission task, only. However with the increasing share of renewable energy sources (especially off-shore wind energy) and decreasing share of conventional power plants, this transmission task is changing and new challenges for the transmission grid appear.
In the TYNDP the TSOs already consider these developments and introduce new grid elements and adopted architecture to meet this requirements. Therefore the considered starting grid in 2030 already provides a significantly increased transmission capacity than today’s system.

In the e-Highway 2050 the scenarios forecast different degrees of transition in the energy system towards a CO_2-neutral energy supply. All of these developments change the energy mix and the demand situation, but not all change the transmission task in the same way. Out of the five scenarios X-5 and X-7 lead to the most severe changes. Both are characterized by a very high share of renewable energy sources, which are mainly centralized technologies[5]. Both expect a strong European-wide cooperation in energy policy that lead to high load flows between the countries and thus increased distances between the generation and the demand. This is also the case in the other scenarios (as it is in the TYNDP-scenarios) but the evolution in X-5 (Large Scale RES) and X-7 (100% RES) goes much beyond what the starting grid in 2030 is designed for. This can be seen in figure 6, where installed capacities and energy balances per country for the two scenarios are shown.

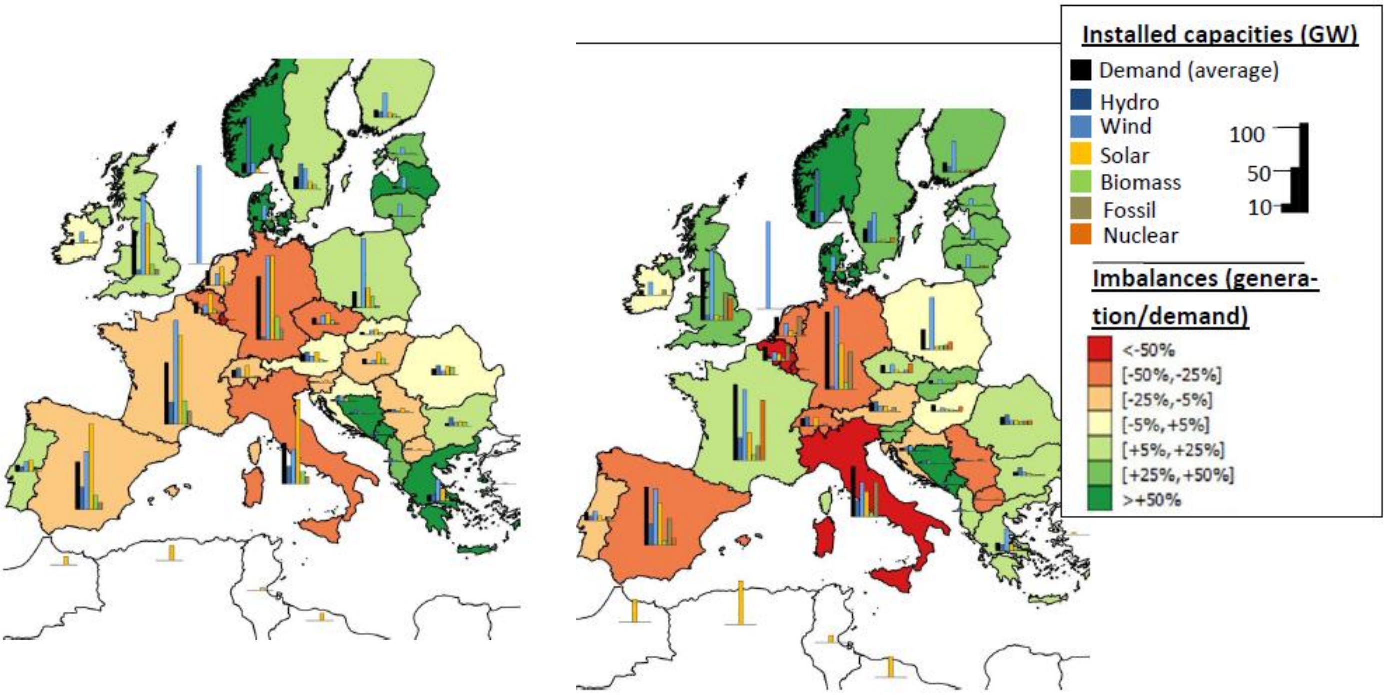


Figure 6: Installed capacities and balances for Scenarios X-7 (left) & X-5 (right)

Based on these energy scenarios, in task 2.3 reinforcements have been defined, that allow interchanges of electricity as they are expected in the given scenarios. Figure 7 shows the significant increase of interconnection capacity towards 2050 within central Europe, which is required to fulfill the transmission task in these scenarios. It goes far beyond the already scheduled planned development for 2030 as it is forecasted in the TYNDP (shown in grey).

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[5] Centralized renewable technologies are mounted in a large scale way, to produce electric energy in regions with high expected gain, which are not usually close to demand. In contrast decentralized renewable technologies, are those mounted on distribution grid level close to demand – usually with less expected gain.

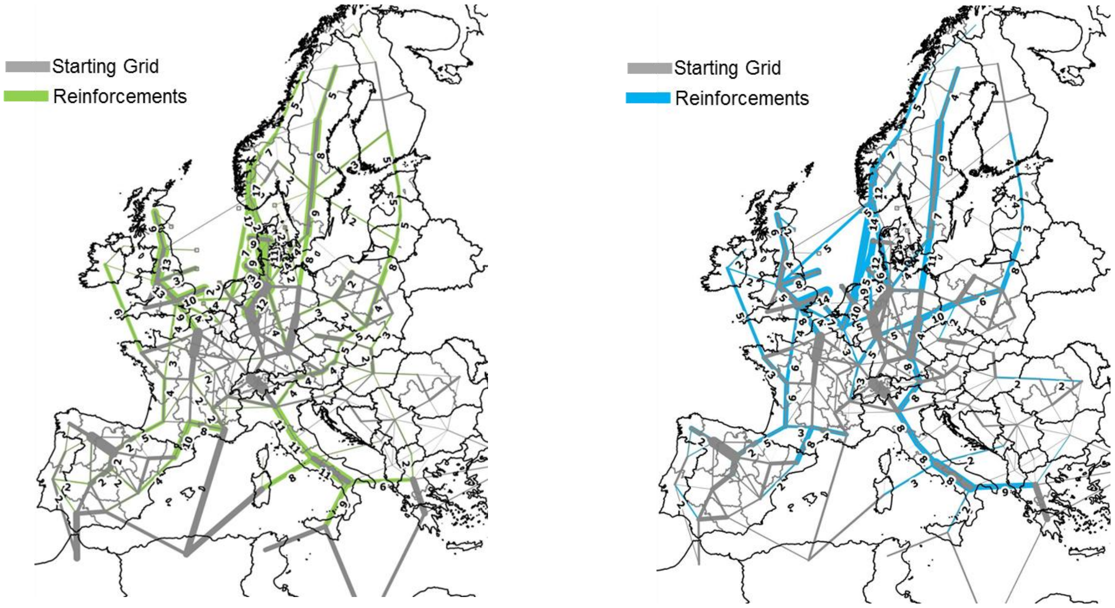

Figure 7: Target Grid Architecture for Scenarios X-5 & X-7

This leads to the effect that the current system as it is today and planned for 2030 is not designed to handle such massive load flows as they would be required in developments forecasted in scenarios X-5 and X-7. These kinds of energy system call for new standards and guidelines for grid planning. Such are:

- Extended contingency criteria for bulk power transmission corridors

  The current most important contingency criteria for grid development is the N-1 security criterion. Grid is planned in such a way that one element may malfunction and still the security of system must be assured. In future systems, where more importance to transnational energy exchanges is given this main transmission lines are a crucial part of the system. It is therefore recommended to extend the contingency analyses for them - a default of these **plus** one other element. (real N-2 or N-1` criterion)
- Assume sufficient initial market capacities between countries

  As it is depicted, particularly in X-5 and X-7, the European energy system depends on large energy exchanges between countries. Both to distribute the renewable production across Europe and to assure security of supply. Since in such scenarios high exchanges result on a top down planning perspective they require higher transmission capacities as existent today. In unit commitment and generation dispatching optimization this leads then to new requirements for exchange capacities and thus grid capacities
- Allow increased In- or Export margins

  Today most of the countries achieve a high degree of independent system adequacy – so the possibility to supply its own demand to a particular extent. Accordingly the generation capacities are almost sufficient to allow a *neutral* balance of the country. It is assumed in scenarios like X-5 and X-7 that the balances of countries vary very much, where some countries are highly importing while others are exporting. This naturally leads to more flows between countries and thus higher flows on the transmission system.

Therefore the load flow situations of scenarios X-5 and X-7 are extremely different from the base case taken (2030). The current practices for performing AC load flows are not designed to handle so different situations from the base case. As a result, no convergence for them could be found. More advanced methods are necessary to simulate those scenarios. This should not be understood as it will not be possible to reach such system in the year 2050, only that R&D on the planning and simulations standards for such scenarios is necessary.

4.2. Considered Grid Elements and Counter Measurement Application

The originally received CIM-Dataset, which is the basis for grid analyses also within ENTSO-e, contains around 15.000 grid elements that are distributed among all continental European countries and throughout all voltage levels ≥ 150 kV. For the transmission grid development planning not all these elements are an issue, this is why a selection, focusing on the most interesting elements, has been made. In detail:

- **Voltage Level:**
  For long term grid development planning of the transmission system only elements have been considered with a rated voltage of at least 220kV. These seem the relevant elements when forecasting towards 2050. Lower voltage levels are not interesting for these analyses.
- **Element-Type:**
  There different kinds of elements in the transmission system. They can be separated to active (Phase-Shifting transformers, HVDC-Terminals, FACTs, etc…) and passive elements (transformers, OHL, cables, etc…). For analyses in task 2.4 the focus was laid on passive elements, since no operating-strategy is needed for those. Their application leads to the same effects in all strategies, what makes the results comparable.

This limits the number of elements to be analyses significantly and makes the problem feasible and results comprehensible.

To detect the required counter measurements the assessment is based on the actual overloads of the considered elements in the clusters has been used as main indicator. A separation is based on the technology, defined by element type and voltage level, and the Δ30%-criterion has been used as detector for constraints to be healed. (see 2.1.3). In detail the following selection has been applied:

- If for one branch Δ Utilization (loading(N – 1) – loading(N)) ≥ 30%, one parallel branch (line or transformer) is introduced
- If for one branch Δ Utilization (loading(N – 1) – loading(N)) ≥ 60%, two parallel branches (lines or transformers) are introduced
- If for two or more parallel branches Δ Utilization (loading(N – 1) – loading(N)) ≥ 30%, only one parallel branch (line or transformer) is introduced

This selection process was done for the three selected scenarios (X-10, X-13 and X-16), the two strategies and the two snapshots. In total this means a consideration and analyses of 12 situations. For each the number of new lines and new transformers is determined.

4.3. Quantitative analyses of Scenarios

In the following descriptions each scenario will be introduced and which target grid architecture has been developed for it in task 2.3. Based on this, the common grid constraints for each strategy are highlighted, so the problems, which appear in either in the “summer low” and/ or the “winter peak” snapshot. Finally the additional costs for cluster internal reinforcements are shown for the strategies in the scenarios

4.3.1. Scenario X-10 – Big & Market

“Internal EU market, EU wide security of supply and coordinated use of interconnectors for cross-border flows exchanges in EU. CCS technology is assumed mature.”

4.3.1.1. Installed Capacities and Balances

In this Scenario, a global agreement for climate mitigation is achieved. Thus, CO2 costs are high due to the existence of a global carbon market. Europe is fully committed to meet its 80-95% GHG reduction orientation by 2050 but it relies mainly on a market based strategy.

Moreover, in this scenario, there is a special interest on large scale centralized solutions, especially for RES deployment. Public attitude towards deployment of RES technologies is indifferent in the EU, while acceptance of nuclear and shale gas, as energy sources, is positive since being preferred to decentralize local solutions. CCS technology is also assumed mature in this scenario.

Among renewables, wind as centralized RES are preferred in this scenario. European demand is 4300 TWh which, compared to other scenarios, is neither high (due to low level of new uses) nor low (due to low efficiency level). The European energy mix (without grid constraints) is presented in Figure 8. It also presents the Figure 8 installed capacities, demand and imbalances per country.

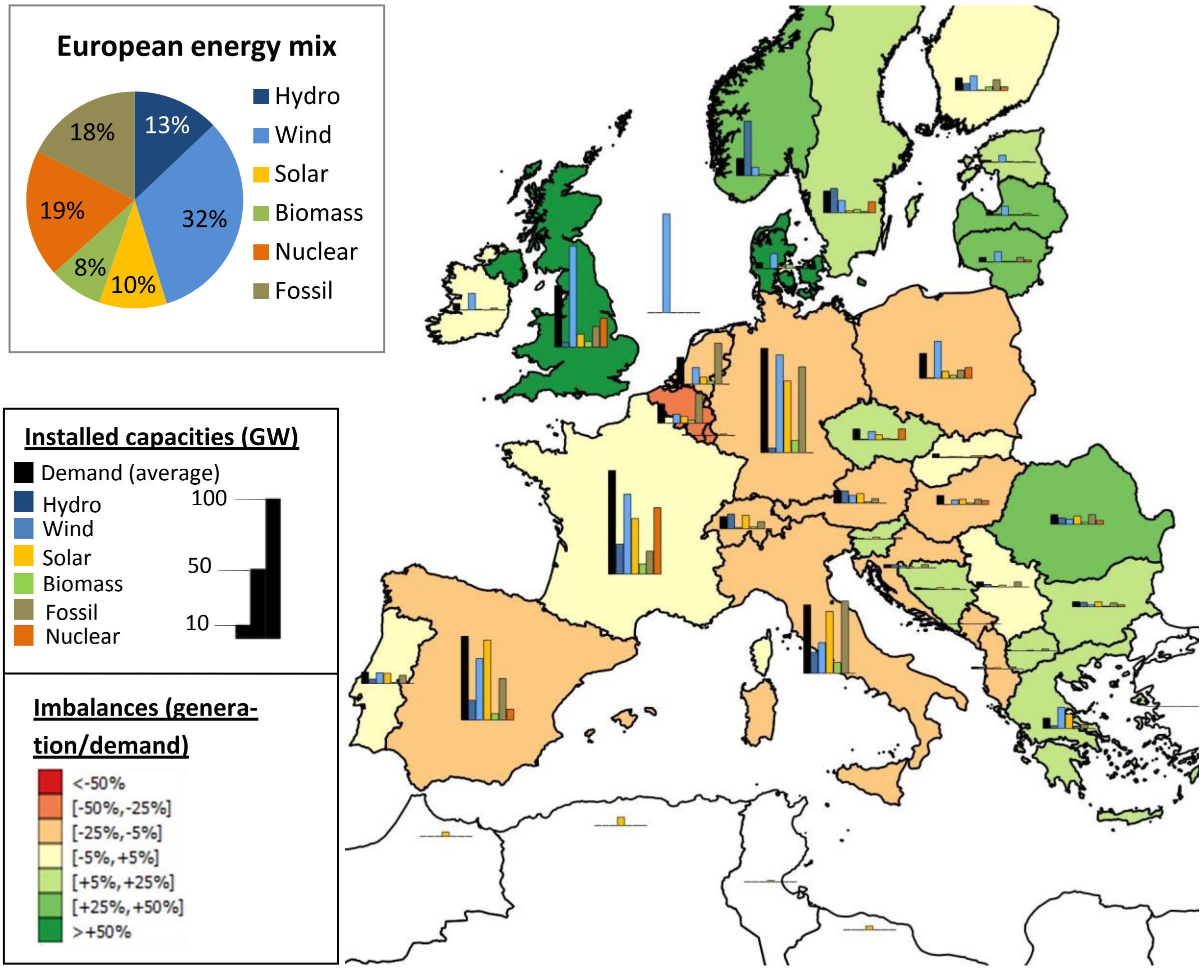

Figure 8: European energy mix, installed capacities and imbalances per country – Big & Market

4.3.1.2. Target Grid Architecture and Main Transmission Corridors

In the scenario X-10 in total 255 GW in new transmission capacity is required, to reach the best trade of between annual investment and operational costs. This presents new corridors of approximately 16.000 km. When the full capacity is deployed the CO2-Emissions reach a total value of 47 Mio. tons each year. Also the “security of supply”-level that is reached in the final grid is within an acceptable thresholds and is reduced to 0 TWh.

Figure 9 shows the required topology with reinforcements of at least 1 GW.

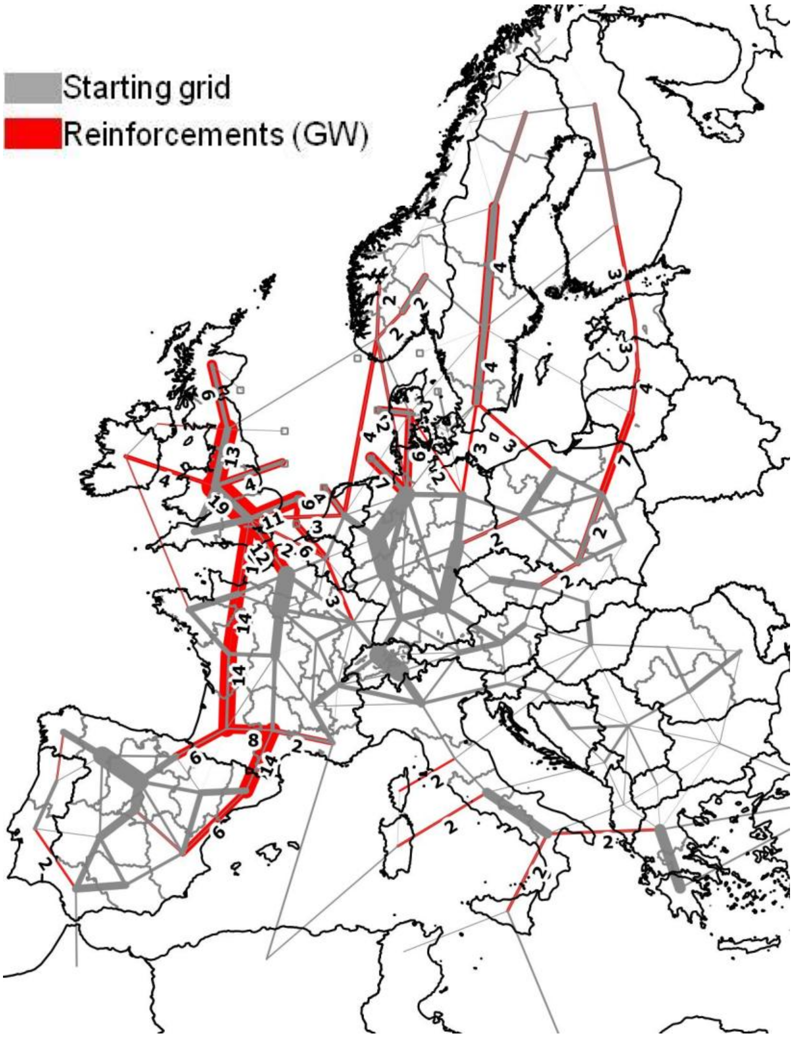

Figure 9: Map of the final grid proposal for the scenario X10

The transmission corridors in X-10 are mainly justified to develop access to “cheap” electricity for the different parts in Europe. Corridors from Scandinavia and UK to continental Europe are built to transport wind and hydro generation, while the corridor to Iberian Peninsula allows both, the transport of solar to continental Europe and the assurance of energy of supply in Spain and Portugal. Figure 10 summarizes the main drivers for these corridors:

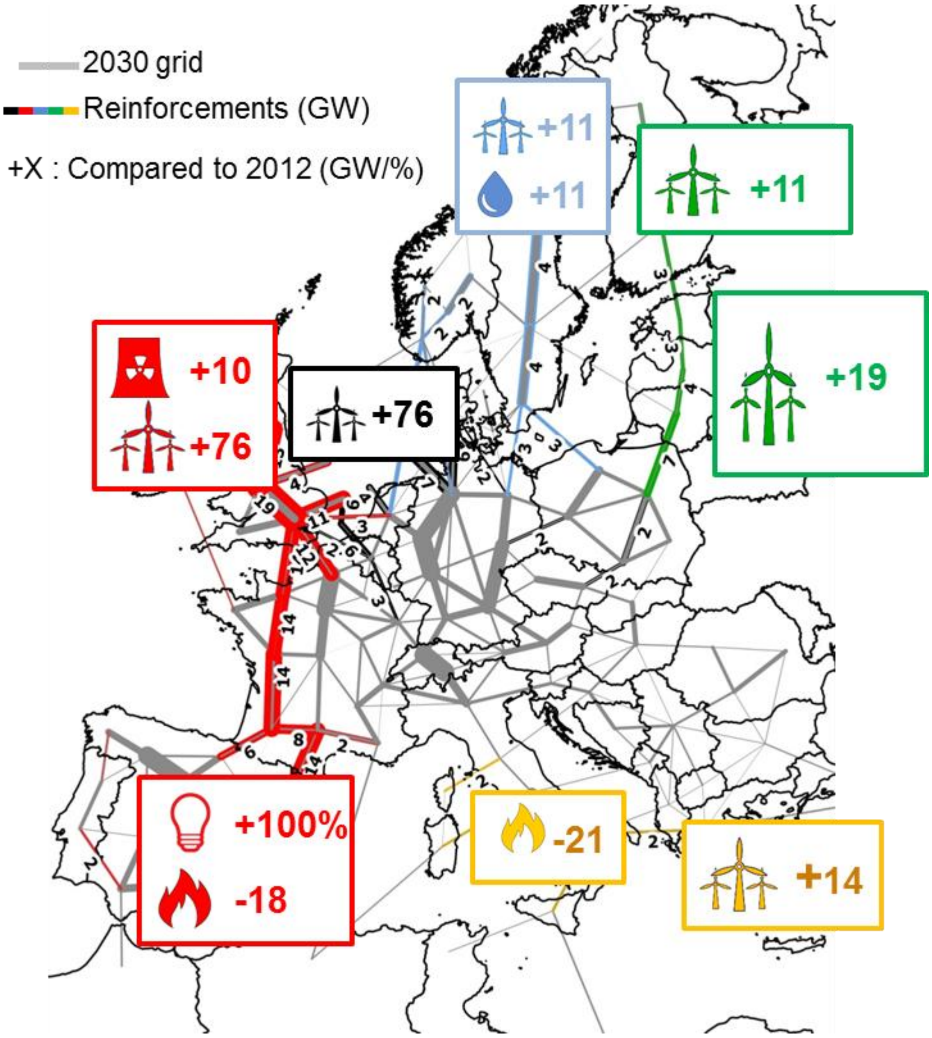

Figure 10: Main Drivers for Transmission Corridors – X-10

4.3.1.3. Constraints in Main Clusters

The resulting grid architectures have been taken and implemented in the grid model that represents the starting situation 2030 in e-Highway 2050. For this it was not only necessary to know the reinforcement capacities but also the technologies to realize them. As has been discussed already in task 2.3 the assumption and the technologies to be implemented follow the chosen strategy. Each strategy assumes a different level of acceptance in the public towards new transmission infrastructure and thus different possibilities for the TSOs to do the grid development. Since AC-load flows have been performed in task 2.4 the included technology has an effect on the grid utilization. Therefore the constraints do vary between the strategies.

Strategy 2 - Re-Use of Corridors

Here new Overhead-lines are allowed what enables grid reinforcements in AC and DC technology. Since AC OHL's are cheaper than DC solutions they are preferred. Therefore strategy 2 is AC dominated

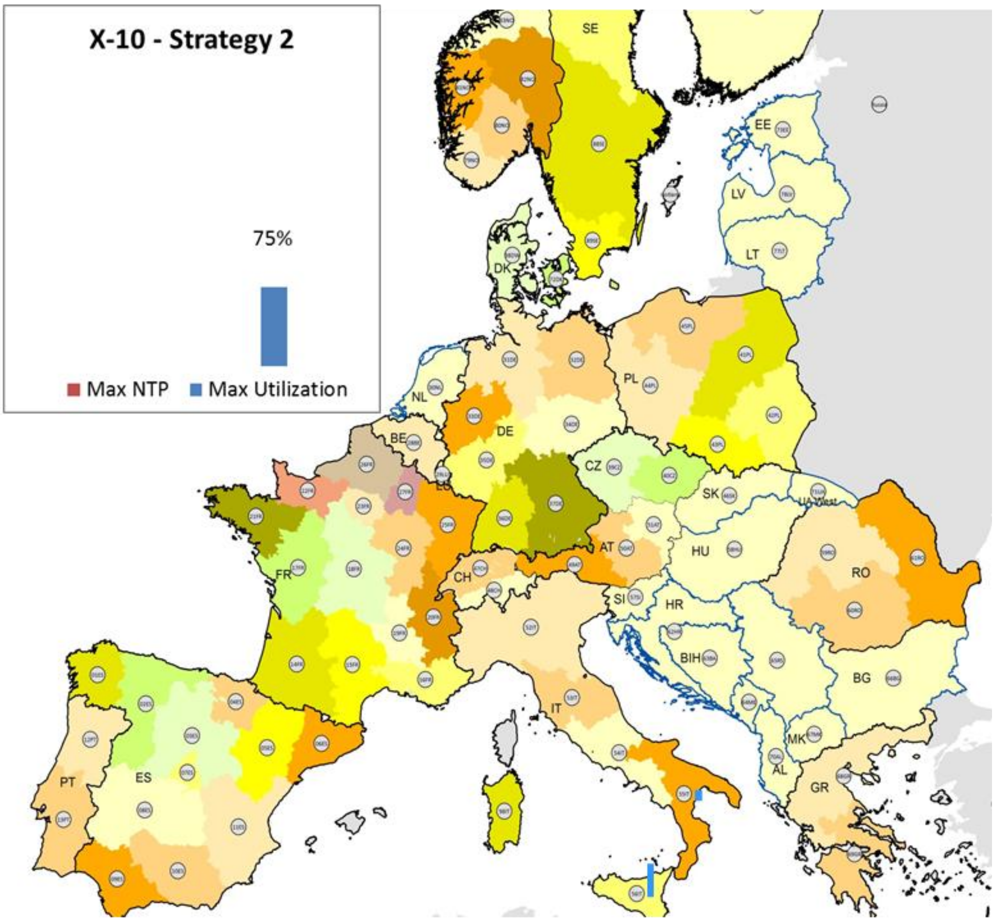

Figure 11: European Grid Constraints Strategy 2 – X-10

It can be seen, that the reinforcements within strategy 2 can be implemented into the system. Judging from the Δ30%-criterion there are no problems in terms of not transmittable power and minor problems in line utilization. Therefore no cluster internal reinforcements are required.[6]

<u>Strategy 3 – Status Quo</u>

Here existing overhead lines can be refurbished to increase the capacity. This allows new AC reinforcements but only with limited capacity. For additional corridors cable are required since public opposition against new corridors is too strong. Given the distances between the clusters only DC cables are technically feasible, therefore strategy 3 is DC dominated

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[6] Shown here and in the following figures, which show the utilizations, is for each cluster the maximum of winter peak and summer low case. An overview of each snapshot-strategy combination individually is given in Annex A.

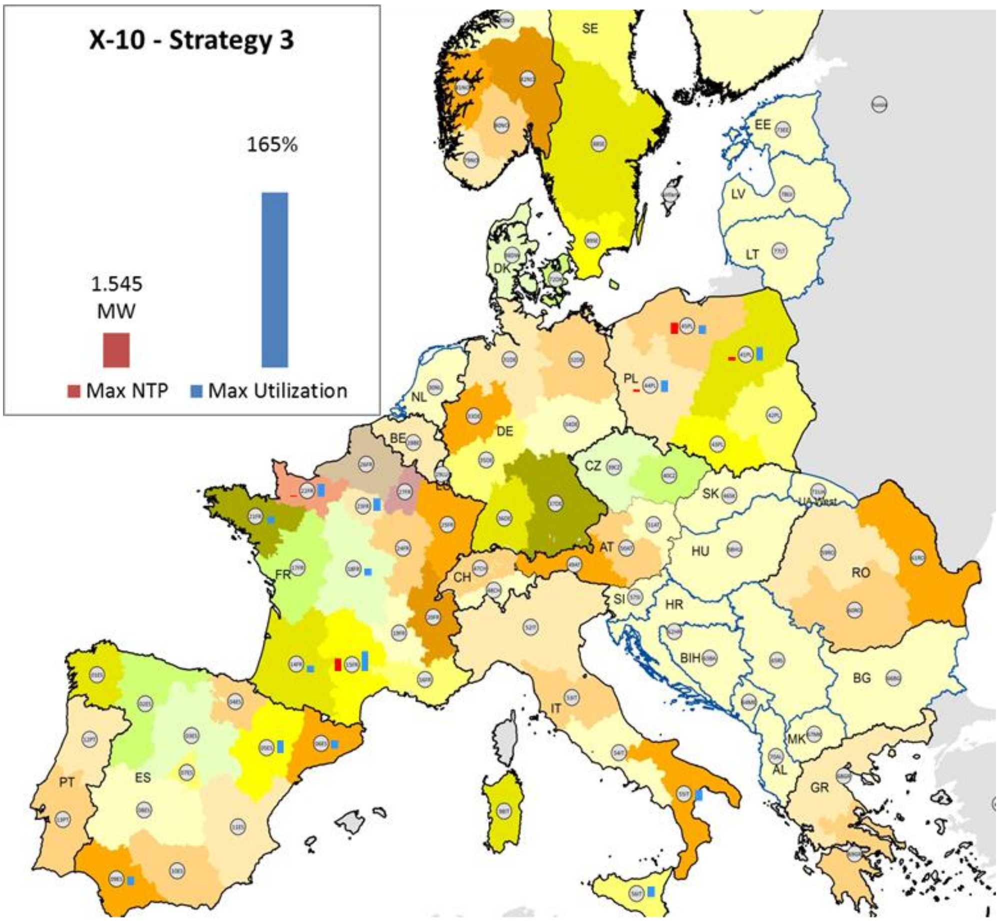

Figure 12: European Grid Constraints Strategy 3 – X-10

Strategy 3, which is the DC dominated variant, requires additional reinforcements within clusters in France, Spain, and Poland. Here we find maximal utilizations of lines that are above the thermal capacity and thus also not transmittable power. The maximal Non-transmittable power reaches a Value of 1.450MW in Poland (cluster 45) which is comparable with one new transmission line and therefore manageable.

Note:
It can be said here already that the Strategy 3, as being a DC Strategy, leads to more constraints in the intra-cluster transmission network than strategy 2, which is AC dominated. This has its main reasons in the “nature” of both transmission technologies. AC is *passive* what means, that the flow on AC elements is dependent on its technical parameters – in comparison to the other AC elements – and the topology of the grid. DC is *active* and the load flow can be controlled what makes the flow on the elements independent from the rest of the system. Also the passivity of AC leads to the case, that in case of a default the whole system “adopts” automatically to the new topology. In case of a large scale integration of DC lines, the flows on the DC lines remain unchanged if no specific control schemes are taken. In order to make DC solutions compatible with a safe operation of the system, new control strategies are required.

4.3.2. Scenario X-13 – Large fossil fuel deployment with CCS and nuclear electricity

“Electrification of transport, heating and industry is considered to occur mainly at centralized (large scale) level. No flexibility is needed since variable generation from PV and wind is low“.

4.3.2.1. Installed Capacities and Balances

In this scenario, a global agreement for climate mitigation is achieved and Europe is fully committed to its target of 80-95% GHG reduction. Thus, CO2 costs are high due to the existence of a global carbon market.

Europe is mainly following a non-RES strategy to reach this target. Acceptance of nuclear and shale gas as energy sources is positive. Nuclear and fossil fuel plants with CCS play pivotal roles in achieving the 80-95% GHG targets without large scale RES deployment. There is a low focus on development of RES and storage solutions.

This scenario is characterized with high demand that reaches 4700 TWh, the second highest demand among analyzed scenarios. The European energy mix (without grid constraints) is presented in Figure 13. It also presents the installed capacities, demand and imbalances per country.

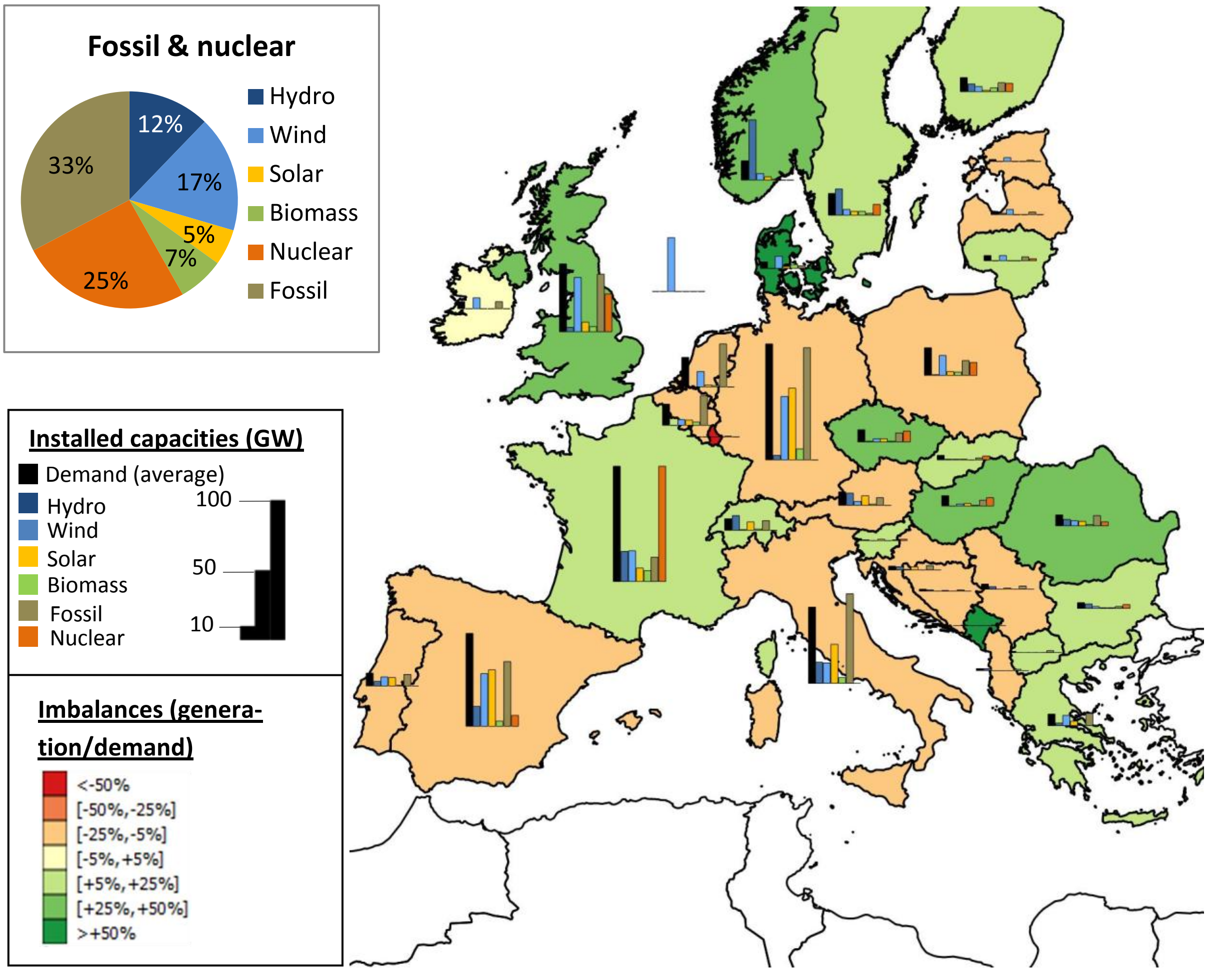

Figure 13: European energy mix, installed capacities and imbalances per country – Fossil & nuclear

4.3.2.2. Target Grid Architecture and Main Transmission Corridors

In the scenario X-10 in total 253 GW in new transmission capacity is required, to reach the best trade of between annual investment and operational costs. This presents new corridors of approximately 21.000 km. When the full capacity is deployed the CO2-Emissions reach a total value of 42 Mio. tons each year. Also the "security of supply"-level that is reached in the final grid is within an acceptable thresholds and is reduced to 0 TWh.

Figure 14 shows the required topology with reinforcements of at least 1 GW.

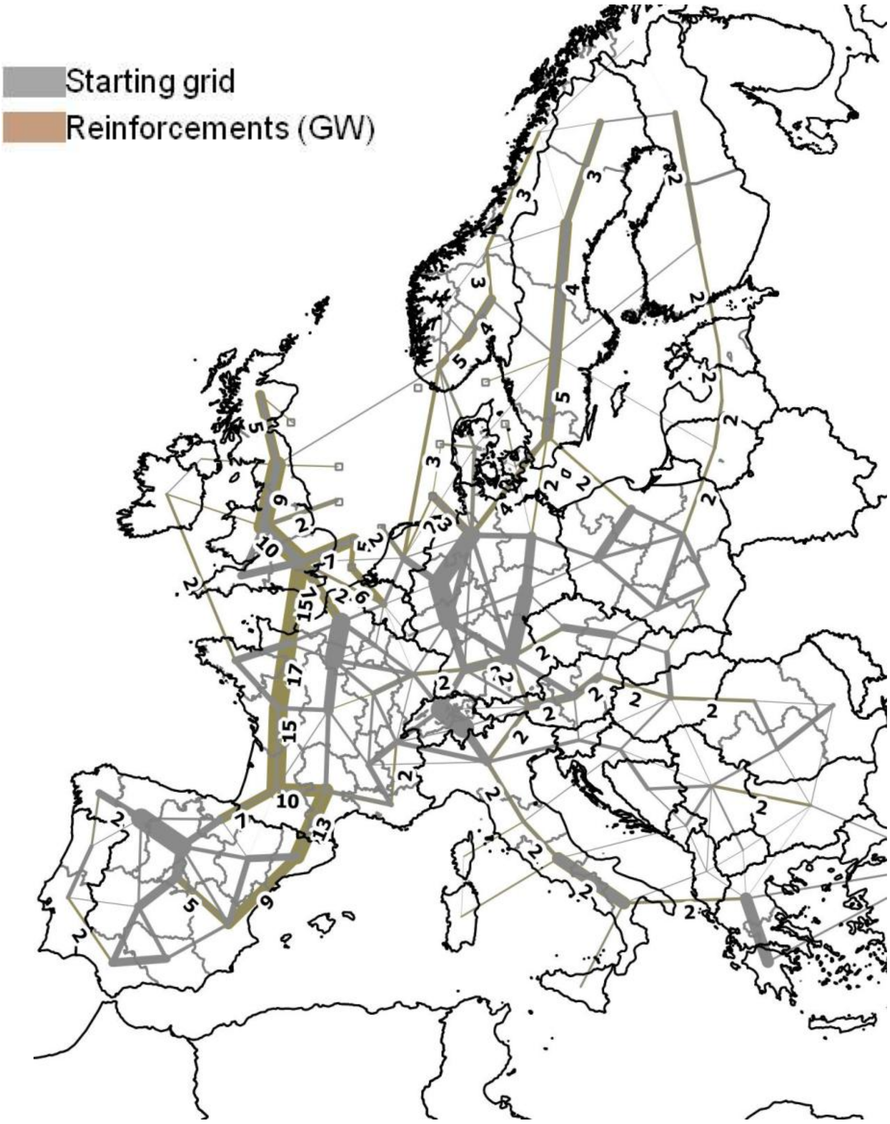

Figure 14: Map of the final grid proposal for the scenario X13

The transmission corridors in X-13 are mainly justified to develop access to "cheap" electricity for the different parts in Europe. Corridors from Scandinavia and UK to continental Europe are built to transport wind and hydro generation, while the corridor to Iberian Peninsula allows both, the transport of solar to continental Europe and the assurance of energy of supply in Spain and Portugal.

4.3.2.3. Constraints in Main Clusters

The resulting grid architectures have been taken and implemented in the grid model that represents the starting situation 2030 in e-Highway 2050. For this it was not only necessary to know the reinforcement capacities but also the technologies to realize them. As has been discussed already in task 2.3 the assumption and the technologies to be implemented follow the chosen strategy. Each strategy assumes a different level of acceptance in the public towards new transmission infrastructure and thus different possibilities for the TSOs to do the grid development. Since AC-load flows have been performed in task 2.4 the included technology has an effect on the grid utilization. Therefore the constraints do vary between the strategies.

Strategy 2 - Re-Use of Corridors

Here new Overhead-lines are allowed what enables grid reinforcements in AC and DC technology. Since AC OHL's are cheaper than DC solutions they are preferred. Therefore strategy 2 is AC dominated

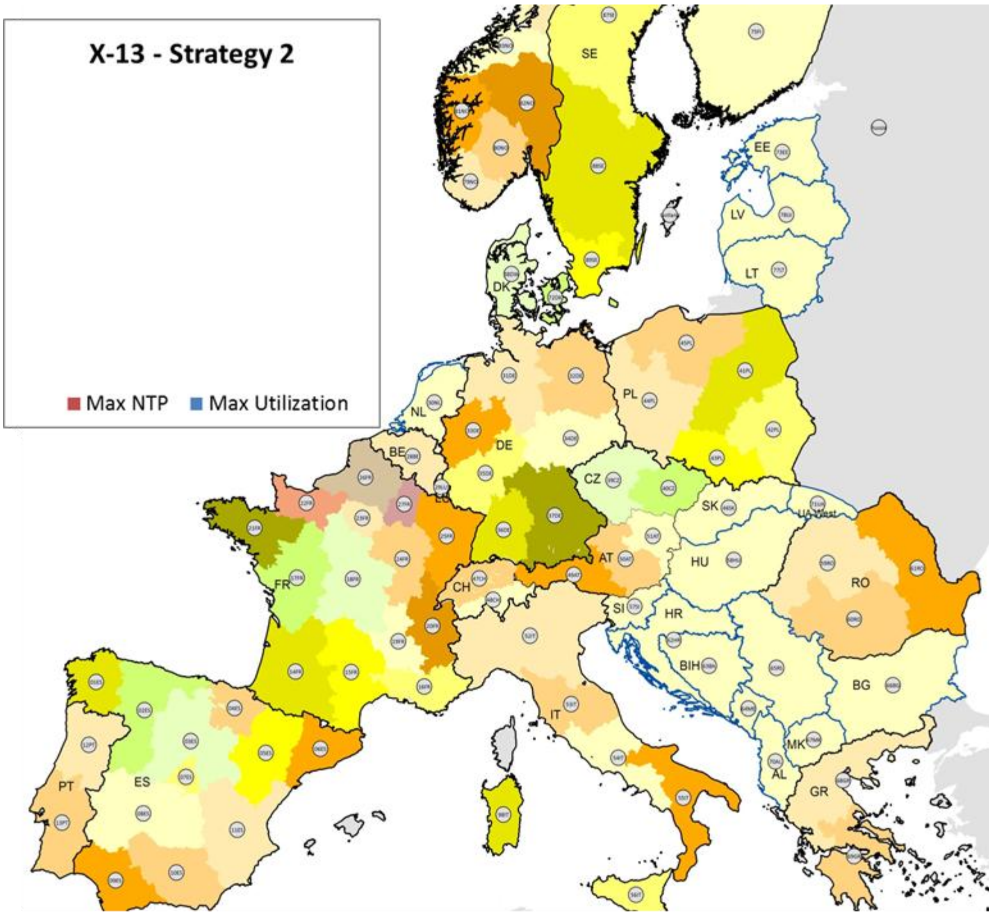

Figure 15: European Grid Constraints Strategy 2 – X-13

It can be seen, that the reinforcements within strategy 2 can be implemented into the system. Judging from the Δ30%-criterion there are no problems in terms of line utilization or not transmittable power. Therefore no cluster internal reinforcements are required.

Strategy 3 – Status Quo

Here existing overhead lines can be refurbished to increase the capacity. This allows new AC reinforcements but only with limited capacity. For additional corridors cable are required since public opposition against new corridors is too strong. Given the distances between the clusters only DC cables are technically feasible, therefore strategy 3 is DC dominated

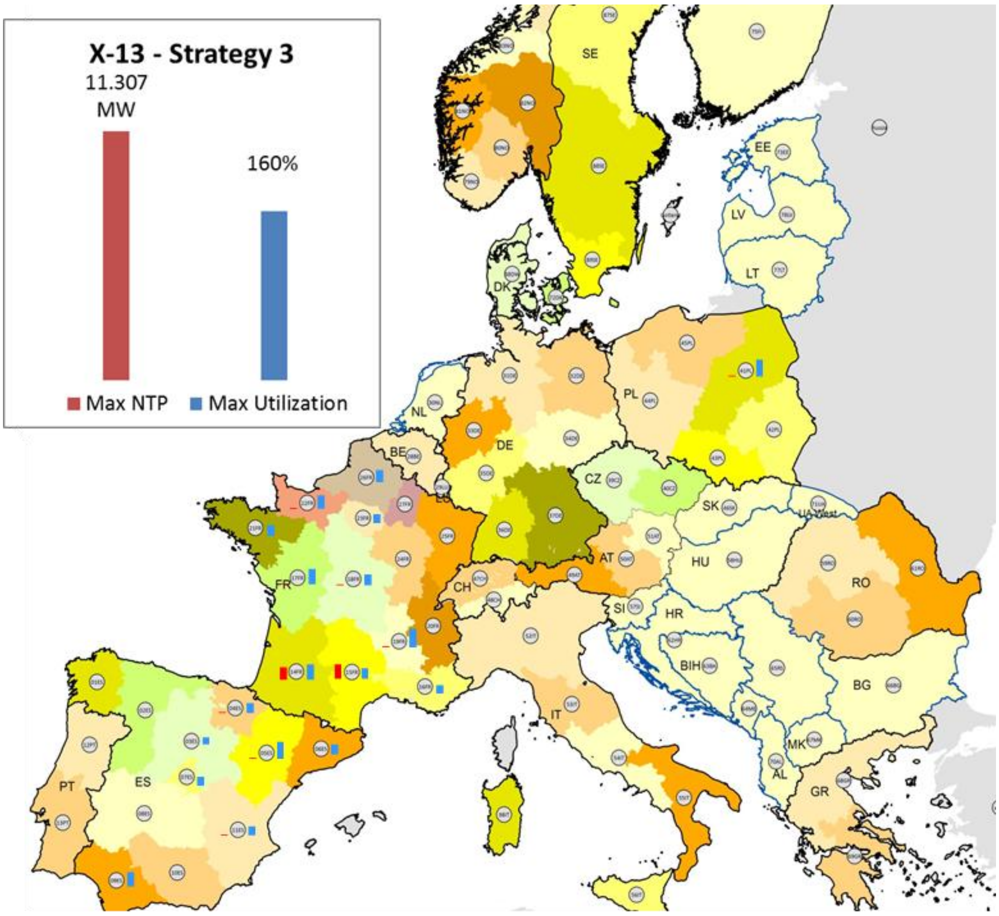

Figure 16: European Grid Constraints Strategy 3 – X-13

Strategy 3, which is the DC dominated variant, requires additional reinforcements within clusters in France, Spain, and Poland. Here we find maximal utilizations of lines that are above the thermal capacity and thus also not transmittable power. The maximal Non-transmittable power reaches a Value of 1.700MW in Spain (cluster 15) which is comparable with one new transmission line and therefore manageable.

4.3.3. Scenario X-16 – Small Scale & Local

“The focus is on local solutions dealing with de-centralized generation and storage and smart grid solutions mainly at distribution level.“

4.3.3.1. Installed Capacities and Balances

In the scenario *Small & local*, the global community has not succeeded in reaching an agreement for climate mitigation. Yet, Europe is fully committed to meet its target of 80-95% GHG reduction. Compared to the other scenarios, the European member states have chosen a bottom-up strategy mainly based on small-scale/local solutions to reach this target.

Common agreements/rules for transnational initiatives regarding the operation of an internal EU market, EU wide security of supply and coordinated use of interconnectors for transnational energy exchanges do not exist. In this scenario, there is a high focus on deployment of de-centralized storage and RES solutions (including biomass), while nuclear and CCS are not considered as options to reach the GHG emission reduction target. The public attitude towards the deployment of local de-centralized RES technologies is positive in the EU.

60% of the demand is covered by decentralized RES, while centralized RES fulfil 25% of the demand. Fossil fuel-fired power plants and nuclear power plants cover 5%, respectively 10% of the demand. X-16 is the scenario with the lowest annual demand (3200 TWh per year) amongst the scenarios considered in the e-highway2050 project. The European energy mix (without grid constraints) is presented in Figure 17. It also presents the installed capacities, demand and imbalances per country.

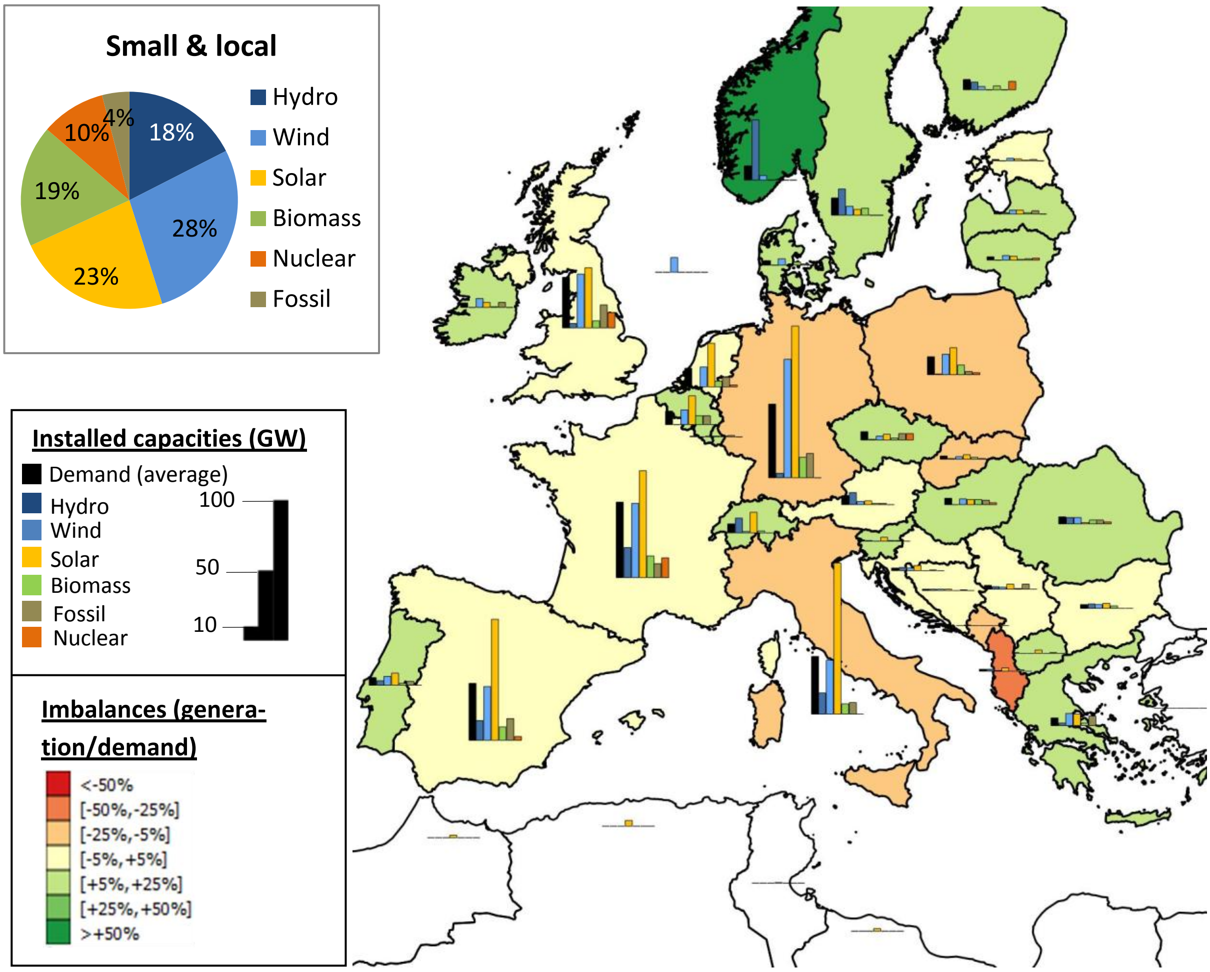

Figure 17: European energy mix, installed capacities and imbalances per country – Small & local

4.3.3.2. *Target Grid Architecture and Main Transmission Corridors*

In the scenario X-16 in total 190 GW in new transmission capacity is required, to reach the best trade of between annual investment and operational costs. This presents new corridors of approximately 16.000 km. When the full capacity is deployed the CO2-Emissions reach a total value of 44 Mio. tons each year. Also the “security of supply”-level that is reached in the final grid is within an acceptable thresholds and is reduced to 0 TWh.

Figure 18 shows the required topology with reinforcements of at least 1 GW.

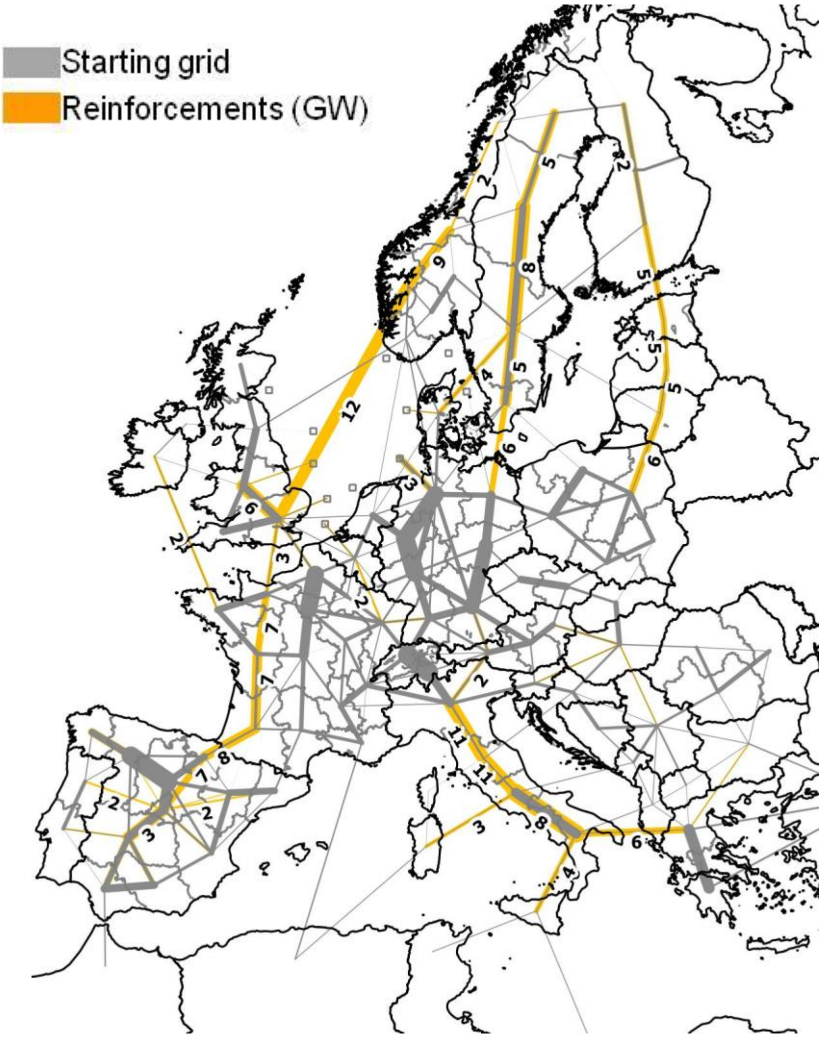

Figure 18: Map of the final grid proposal for the scenario X-16

The transmission corridors in X-16 are mainly justified by ENS issues, which needed to be eliminated and to develop access to “cheap” electricity for the different parts in Europe. Corridors from Scandinavia and UK to continental Europe are built to transport wind and hydro generation, while the corridor to Iberian Peninsula allows both, the transport of solar to continental Europe and the assurance of energy of supply in Spain and Portugal. Also the inner-Italian back-bone plays a major role to include solar production in the central continental system and to support security of supply in Italy. Figure 19 summarizes the main drivers for these corridors:

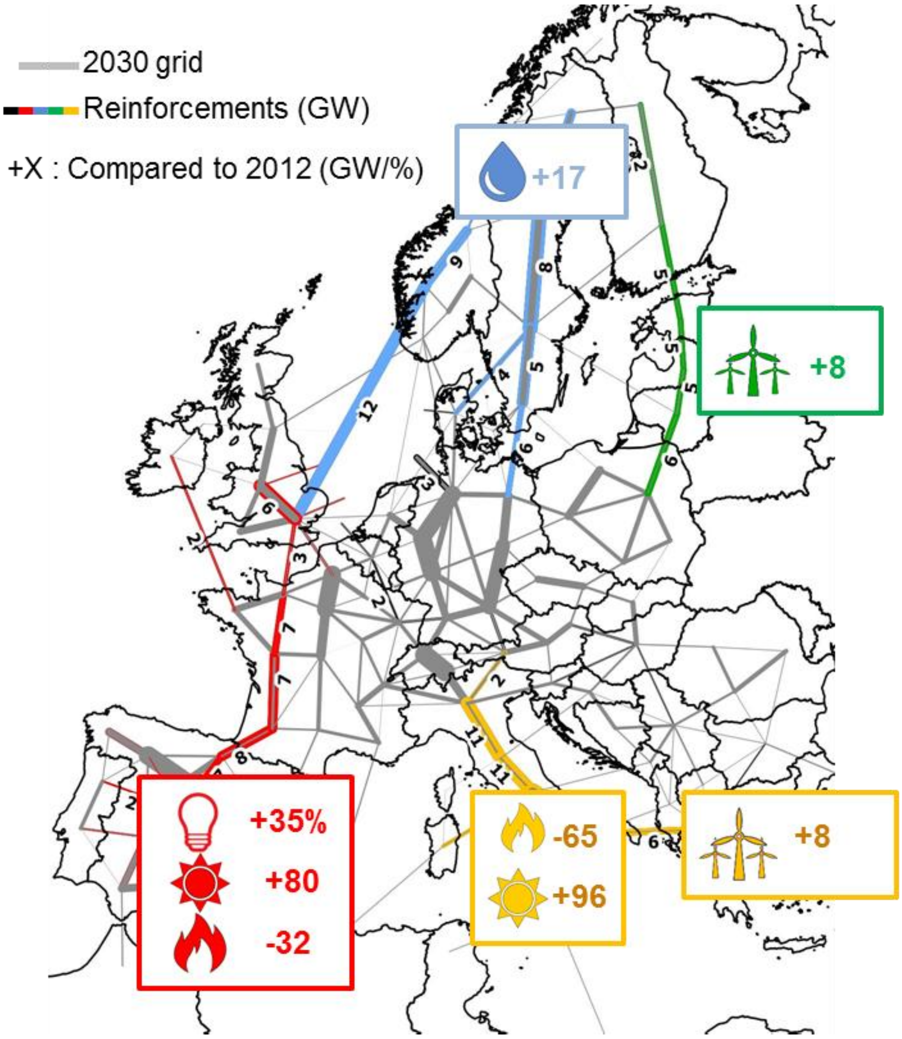

Figure 19: Main Drivers for Transmission Corridors – X-16

4.3.3.3. Constraints in Main Clusters

The resulting grid architectures have been taken and implemented in the grid model that represents the starting situation 2030 in e-Highway 2050. For this it was not only necessary to know the reinforcement capacities but also the technologies to realize them. As has been discussed already in task 2.3 the assumption and the technologies to be implemented follow the chosen strategy. Each strategy assumes a different level of acceptance in the public towards new transmission infrastructure and thus different possibilities for the TSOs to do the grid development. Since AC-load flows have been performed in task 2.4 the included technology has an effect on the grid utilization. Therefore the constraints do vary between the strategies.

Strategy 2 - Re-Use of Corridors

Here new Overhead-lines are allowed what enables grid reinforcements in AC and DC technology. Since AC OHL’s are cheaper than DC solutions they are preferred. Therefore strategy 2 is AC dominated

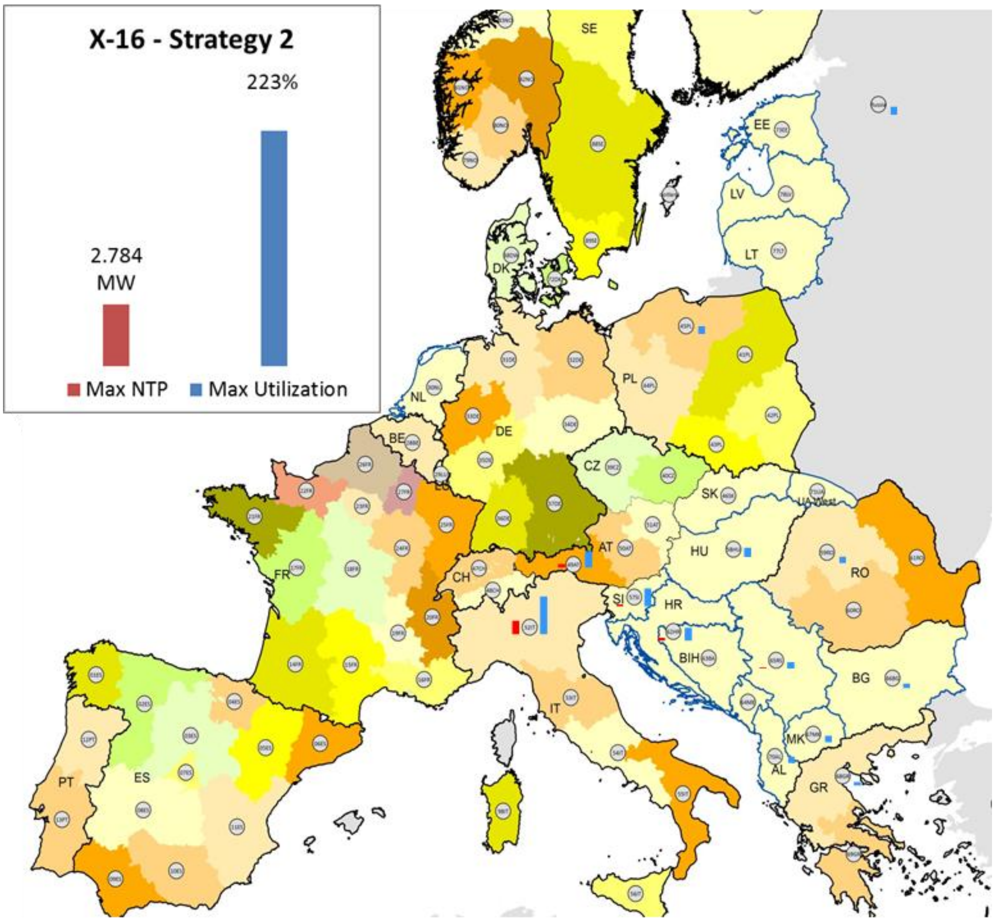

Figure 20: European Grid Constraints Strategy 2 – X-16

In case of scenario X-16 also problems in strategy 2 appear in the grid. There are problems in Northern Italy which are caused by the flows of to Italy to assure supply of energy in the winter-peak situation. The main transmission corridor through Italy "starts" here and the power flows go through the north Italian grid that is not capable of handling them. The Situation in the Balkan Areas is that energy is imported from (and through) Italy via the sub-sea cables which is then stressing the lines in Croatia and Bosnia. Also here further internal reinforcements are required.

<u>Strategy 3 – Status Quo</u>

In this strategy existing lines can be refurbished to increase the capacity. This allows new AC reinforcements but only with limited capacity. For additional corridors cables are required since public opposition against new corridors is too strong. Given the distances between the clusters only DC cables are technically feasible, therefore strategy 3 is DC dominated

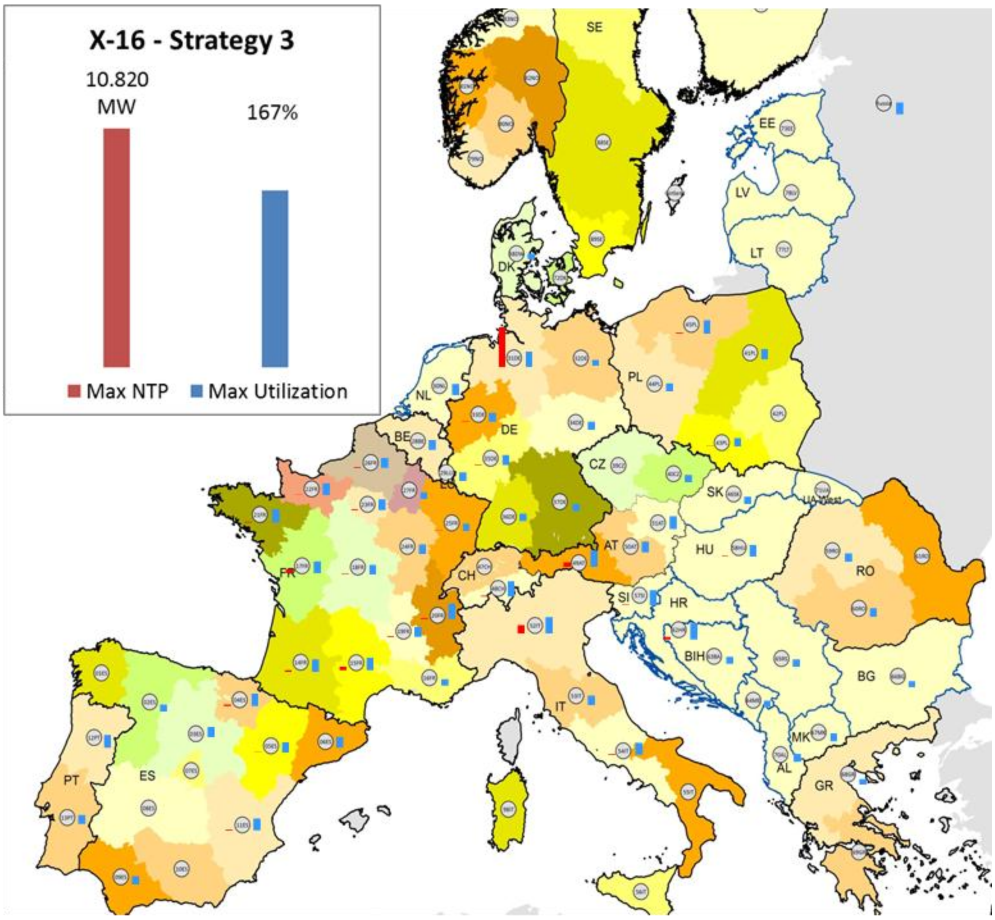

Figure 21: European Grid Constraints Strategy 3 – X-16

Strategy 3, which is the DC dominated variant, shows a quite strong and equally distributed utilization of the internal lines that is caused by the implemented inter-cluster structure. There are constraint lines in all countries, yet the maximum utilization is 167%, thus can be cured with a parallel line (or a double circuit. Another problem is caused by the maximum not transmittable power – a value of 11 GW can’t be transported in cluster 31 (Germany). Here significant additional investments will be required. It is also interesting to include further transmission capacity in the inter-cluster structure.

4.1. Estimated Costs for grid infrastructure

To solve the constraints identified with DC reinforcements but not with AC ones, different control schemes of the HVDC could be tested. This solution could avoid the need for extra investment. However, it could be not studied in T2.4 as the control of so many HVDC embedded in the AC grid is still a research topic.

Costs for Intra-Cluster Reinforcements

The costs of intra-cluster reinforcements are calculated per strategy, assuming the standard costs for additional transmission lines that have been also used in task 2.3[7]. Afterwards they are given as a total value for continental Europe and put into perspective to the costs of the inter-cluster structure. Figure 22 shows the costs situation as it appears for additional reinforcements in the intra-cluster transmission system.

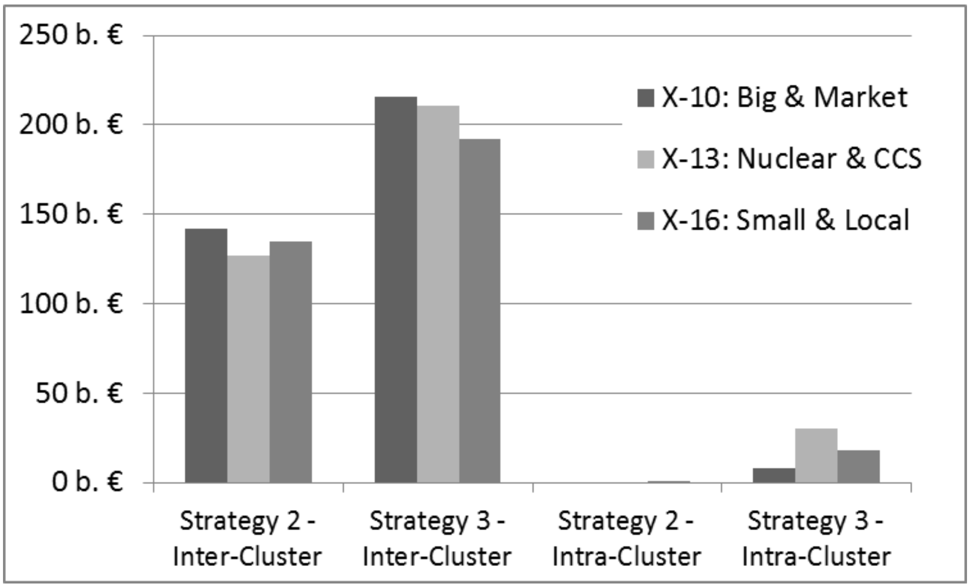

Figure 22: Cost comparison – Inter-cluster Structure and Cluster-Internal Reinforcements

The additional investments to make the architectures operable ranges between 8 b. € in Scenario X-10 and 30 b. € in X-13 (for X-16 it is 18 b. €). If this is put into perspective to the cost for the inter-cluster structure it means an additional surplus of 3.5% to 14.3% of the total costs for grid infrastructure. This and the previous analyses shows, that that the intra-cluster grid is a factor to be considered, but no criteria that prevents an establishment of an inter-cluster structure. Depending on the scenario there are different costs levels, but in a range still allowing a positive benefit of the whole structure. From today's perspective it seems more profitable to implement strategy 2 – the AC solutions – in the system since they cause less additional costs. Maximal are 1 b. € in strategy X-16, while in X-10 and -13 there are no costs. But it remains open if the effort for a DC implementation can be decreased by introducing new operational strategies for controllable DC-connections. This is to be analyzed in later studies.

It must be pointed out, that analyses in task 2.4 only focused on thermal utilization of lines and non-transmittable power. Of course a real implementation in the grid requires further analyses, which probably will reveal different problems that have to be solved. Yet it is expected that the involved costs will also not put the overall benefit into question.

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[7] In Task 2.3 only grid solutions available in 2050 have been considered. 220 kV AC overhead-lines are also available in 2050 but the "state-of-the-art" transmission technology is currently 380kV throughout the European TSO's and there is no technical reason to go back to 220kV. Thus 220kV is not considered in Task 2.3, but it is included in the starting grid data. When 220kV lines or transformers need to be reinforced the same costs as for 380kV are assumed. This means in reality costs would be somewhat lower.

5. Summary and Outlook

The main objective of working package 2 in the e-Highway 2050 project was to define and the verify transmission system structures that are capable to support Europe's energy system towards a sustainable energy and carbon neutral supply. This has been done by a definition of challenging, yet possible scenarios for the year 2050 (2.1). In parallel to the scenario-work a grid model of the pan European transmission system was derived and used for further analyses (2.2). These two inputs where then used in a grid development process in which transmission corridors between clusters in Europe were defined that allow an exchange of energy and finally the reaching of the energy targets in the scenarios (2.3). This inter-cluster gird has been checked for its ability to reach the targets as well as its overall benefit, as it is can be found in the different scenarios. But until this point it was not checked what additional measures are required to assure a save state of operations. To validate this was the objective of task 2.4.

For purpose the results from the previous tasks were taken and included in the starting grid model, which has already been taken to derive the equivalent grid model, developed in task 2.2. Within the model the results of the unit commitment and generation dispatching optimization have been included as well as the final transmission corridors from task 2.3. To determine the final technology to be used best for grid expansion planning for two strategies have been analyzed – one dominated by AC Overhead-Lines, one dominated by DC-cables – and checked for their impact on the intra-cluster grid. The analyses focused on two snapshots for each situation – summer low and winter peak – which represent contrary requirements to the transmission system. In total twelve different situations were calculated and compared.

The analyses revealed three main results:

- The energy sector can evolve in very different ways to a carbon neutral energy supply. The inclusion of very high shares of renewable energy sources, as it is depicted in scenarios X-5 and X-7, represents hereby a breach with the classical energy system which sets new requirements towards transmission system planning. These new requirements are more and more included in current methods for grid development but they will have to play an even more important role once a real development towards RES dominated energy systems can be observed. Under the current planning standards the foreseen grid in 2030 is highly stressed with the flows expected in these scenarios . As a consequence the aims to analyze the effects of scenarios X-5 and X-7 were not successful. This is why work in this deliverable focuses on a qualitative assessment of these scenarios and a suggestion of points that might be considered in future grid development planning.

- The implementation of the DC technology in the pan European transmission system provides challenges and is currently expected to be involved with higher costs. The analyses show, that the implementation of the AC strategy leads to less overloads throughout all scenarios and snapshots. AC lines are "passive" grid elements and the flow they are utilized with is a direct result of the physical parameters and the topology of the whole synchronous transmission grid. Therefore the flows "adapt" automatic to new conditions. On the contrary DC elements are controllable and an operation strategy can be defined for them. This means that flows in these elements do not adapt to new situations but remain within pre-set parameters. The operation strategy of these elements has therefore a high impact on their implementation in the existing system. In the current state this can lead to in-efficient operation causing more constraints. New operation strategies may improve this situation, but their development was not in focus of the analyses performed here.

- The main component of the transmission systems in the future are the main inter-cluster transmission links, which allow a transport of energy between the regions of Europe. They generate the main part of the benefit of the transmission system but are also responsible for the majority of investment needs. It could be shown that the required intra-cluster reinforcement play a less significant role for the overall costs. Even in the case of strategy 3, where most constraints appear the required costs are below one fifth of the total costs.

As a final conclusion it can be said, that the implementation of an inter-cluster system is an economical feasible way to reach the EU's objective and its climate targets in the year 2050. The CO2-targets can be met and the transmission system can support energy exchanges across Europe – providing both, an increased security of supply and an integrated EU market. The costs of transmission elements are compensated by their promised benefits, which is the case for inter-cluster as well as for intra-cluster reinforcements. From today's perspective the implementation of AC-Technologies seems to be the easier and cheaper way to reach the final grid architectures, but with new operation strategies of the controllable DC elements this statement has to be re-assessed.

Operational aspects of the final grid architectures and proper operational directives are evaluated in working package 4.

6. Annex A: List of considered DC links in Grid the Grid Model

In the used grid model data there are country internal DC links, but in case of Germany. These have been implemented in the model. In the table below, the left column shows the DC links that had to be identified in the model, and the central and right column show the indications provided by ENTSO-E Working Group *Network Models and Data*.

DC Link	**Terminal 1**	**Terminal 2**
dc28_be - dc33_de	HGUE Lixhe D74-BE	HGUE Oberzier D74-BE
dc31_de - dc33_de	HGUE EMDB	OSTRAT
dc31_de - dc35_de	WEHRND	URBER
dc31_de - dc36_de	HGUE EMDB	HGUE PHILI
dc31_de - dc37_de	HGUE BRUN	HGUE GROGH
dc33_de - dc36_de	OSTRAT	HGUE PHILI
dc34_de - dc37_de	LAU	MEITGN
112_ns - 31_de	DolWin 1	HGUE BRUN

Table 6: Country-Internal *DC link to be identified by Terminals*

Then, a list was constituted with the nodes whose NAME contain a part ‘HGUE’ (German: Hochspannungs-Gleichstrom-Übertragung) and their corresponding clusters. Collating this list with the table above, DC link terminals could be identified.

Annex B: Delta-Utilizations per analyzed snapshot

The delta-utilization of lines in the different clusters has been calculated for each scenario, each strategy and each snapshot. To calculate the delta utilization the analyses have been done in each of these combinations in N and N-1 analyses. In total this means 2 * 2 * 3 * 2 --> 24 sets of grid analyses. For overview purposes in 4.3 the focus was on the maximum of the delta-utilization, between winter peak and summer low. This means that for the figures 11/12, 15/16 and 20/21 that per strategy in each cluster only the maximum value of either WP or SL was shown. To give a full picture on the utilizations here the information for each single situation is given.

X-10: Big and Market - Strategy 2

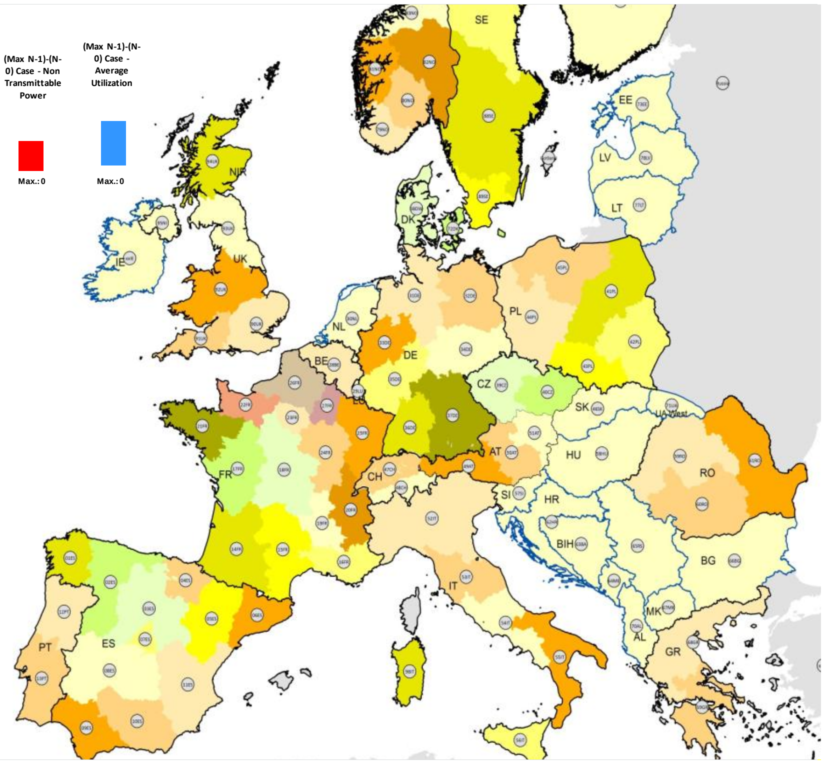

Figure 23: X-10 – Strat 2 – Winter Peak

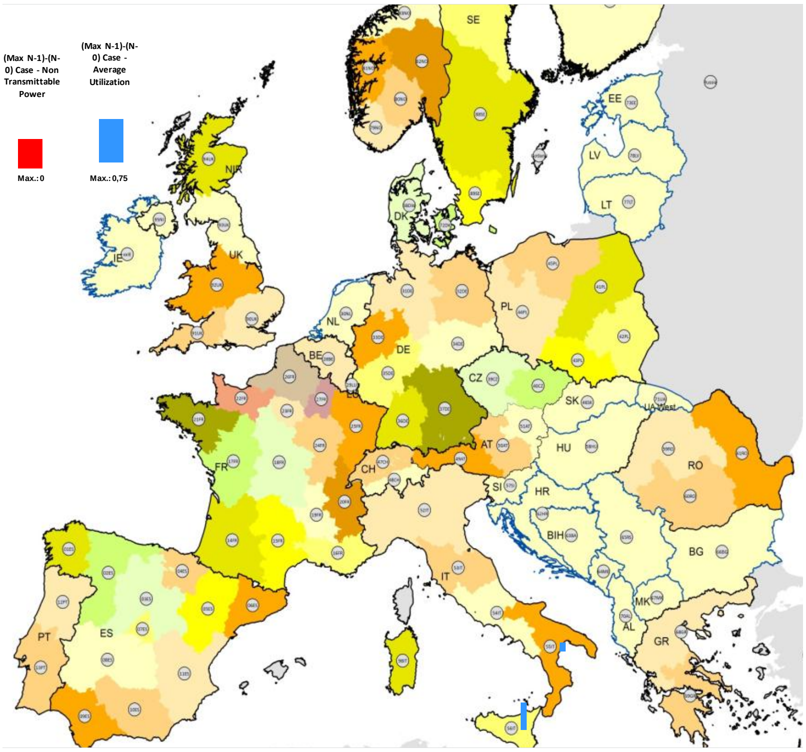

Figure 24: X-10 – Strat 2 – Summer Low

X-16: Small and Local – Strategy 3

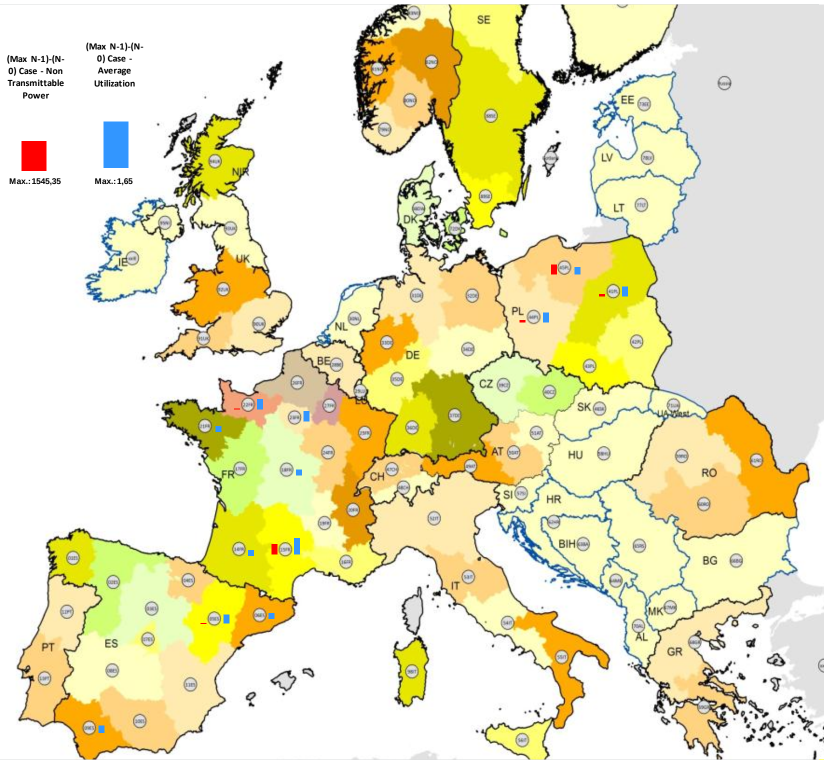

Figure 25: X-10 – Strat 3 – Winter Peak

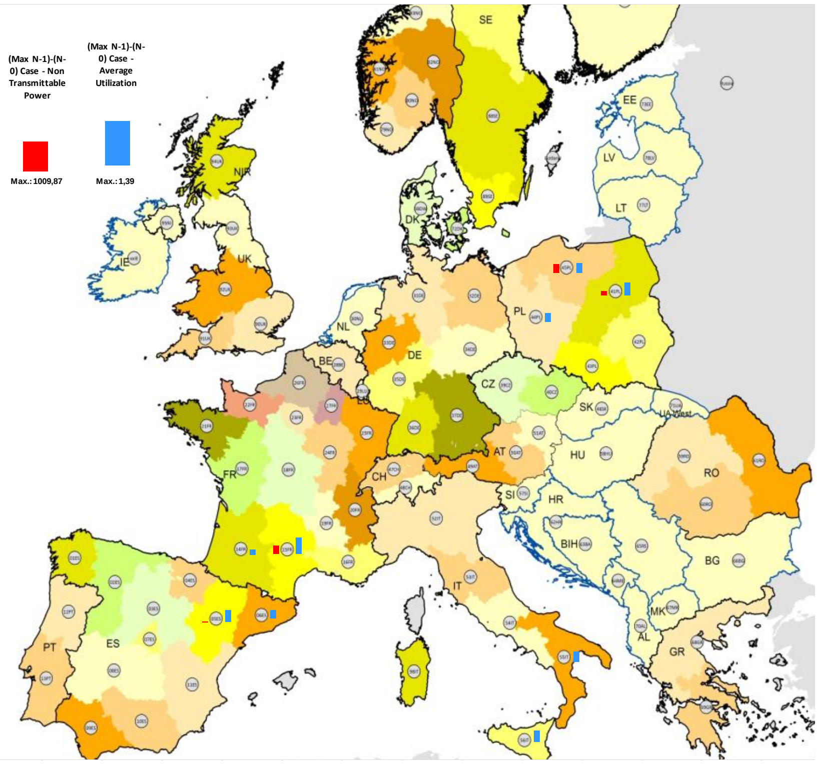

Figure 26: X-10 – Strat 3 – Summer Low

X-13: Nuclear and CCS – Strategy 2

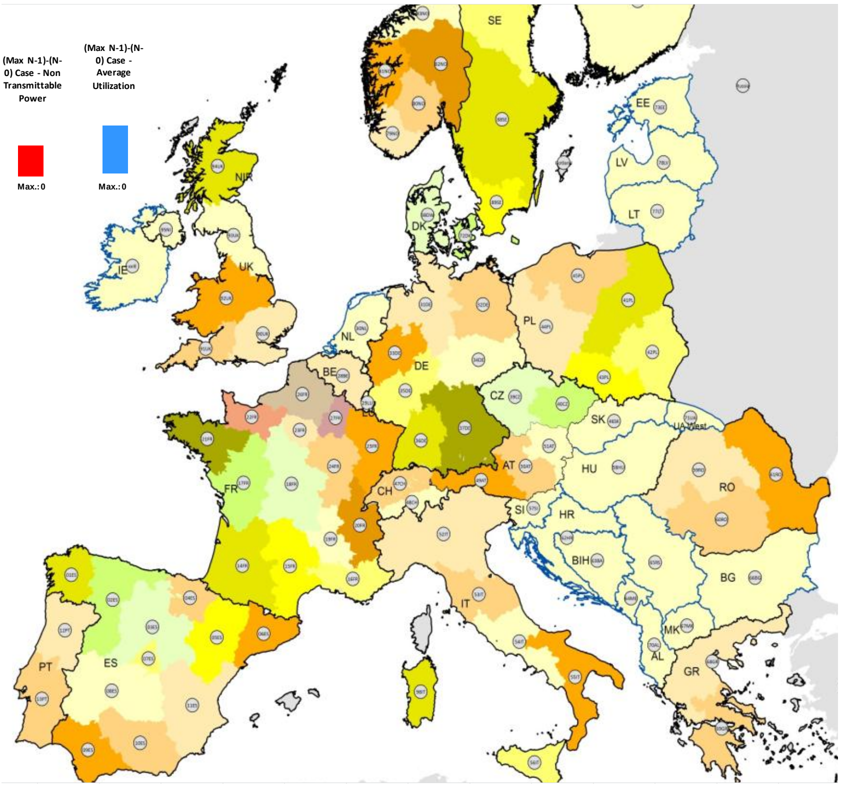

Figure 27: X-13 – Strat 2 – Winter Peak

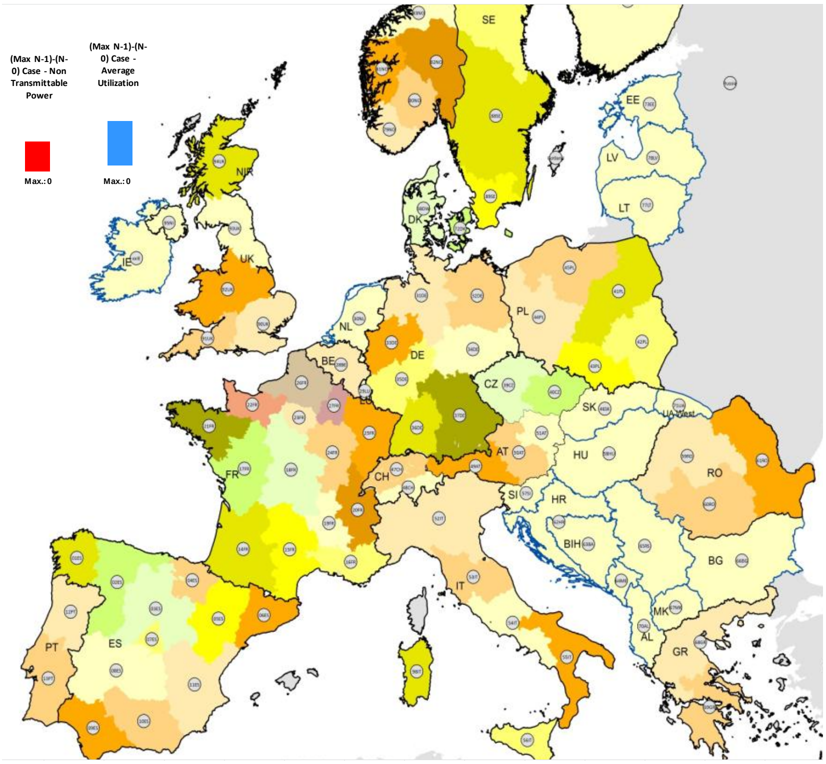

Figure 28: X-13 – Strat 2 – Summer Low

X-13: Small and Local – Strategy 3

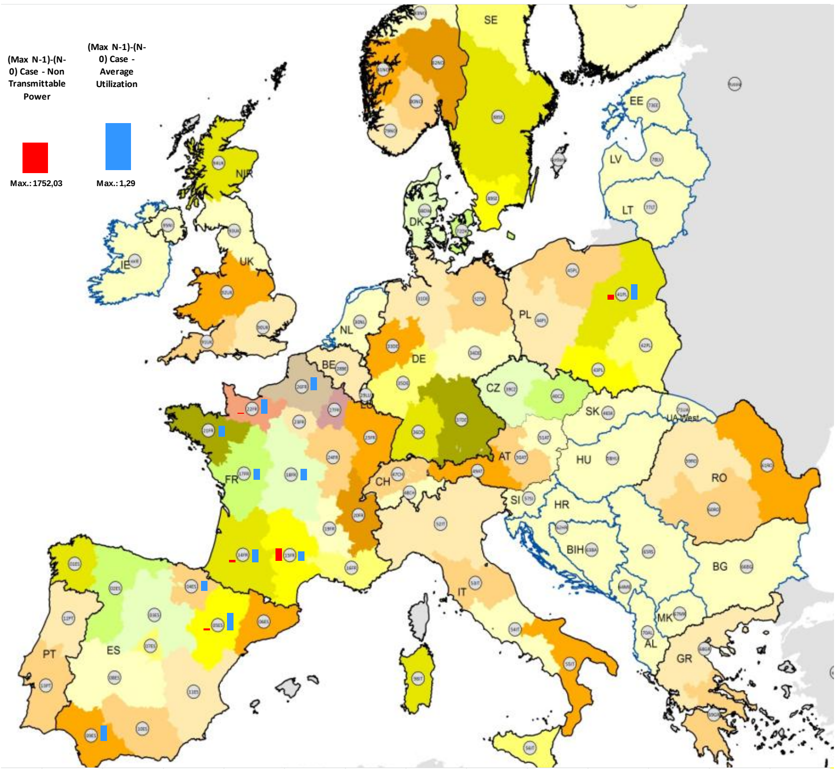

Figure 29: X-13 – Strat 3 – Winter Peak

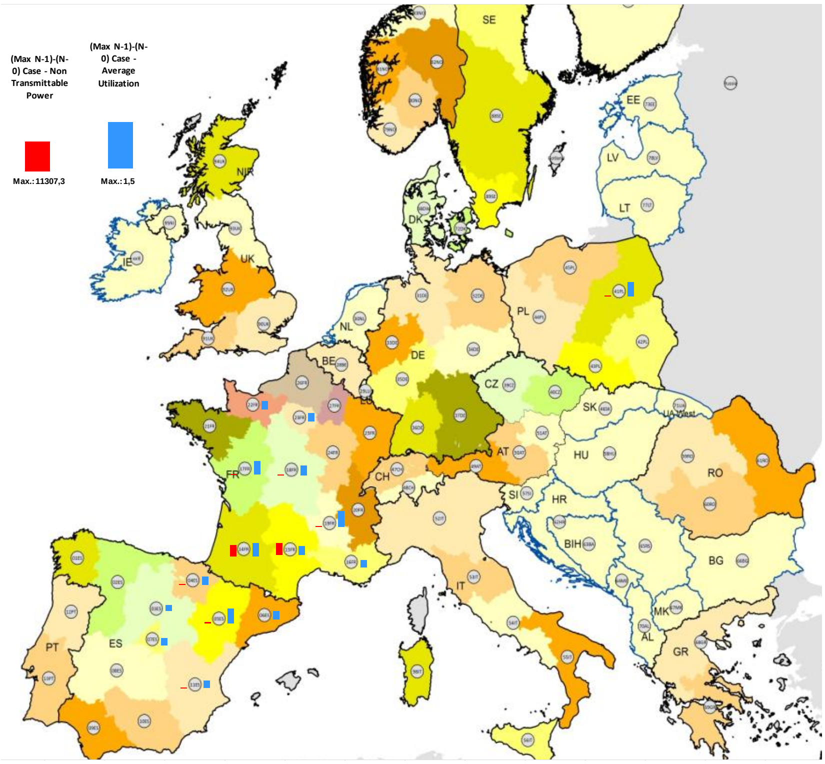

Figure 30: X-13 – Strat 3 – Summer Low

X-16: Small and Local – Strategy 2

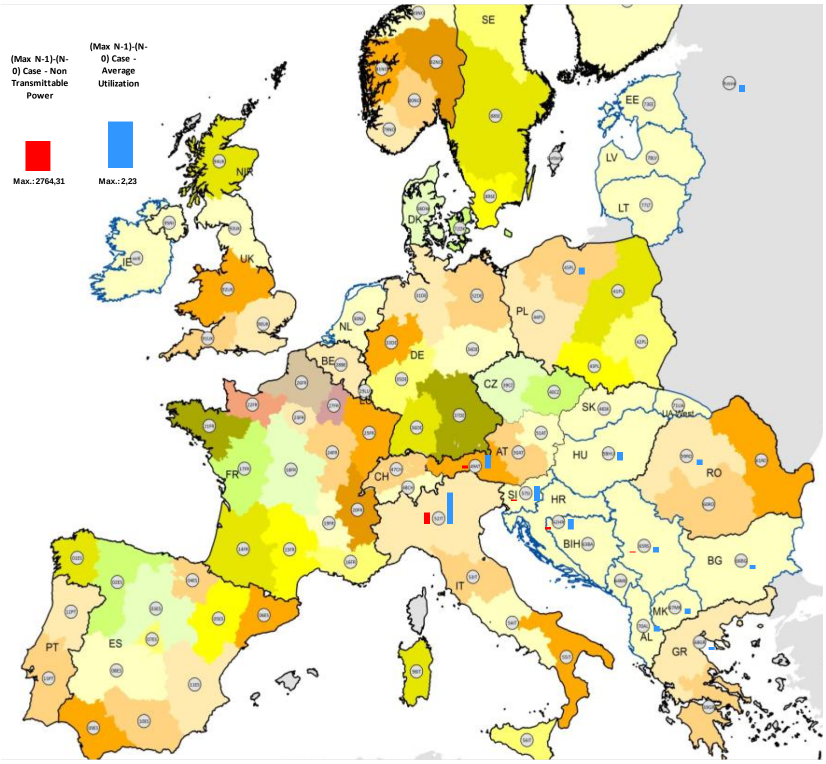

Figure 31: X-16 – Strat 2 – Winter Peak

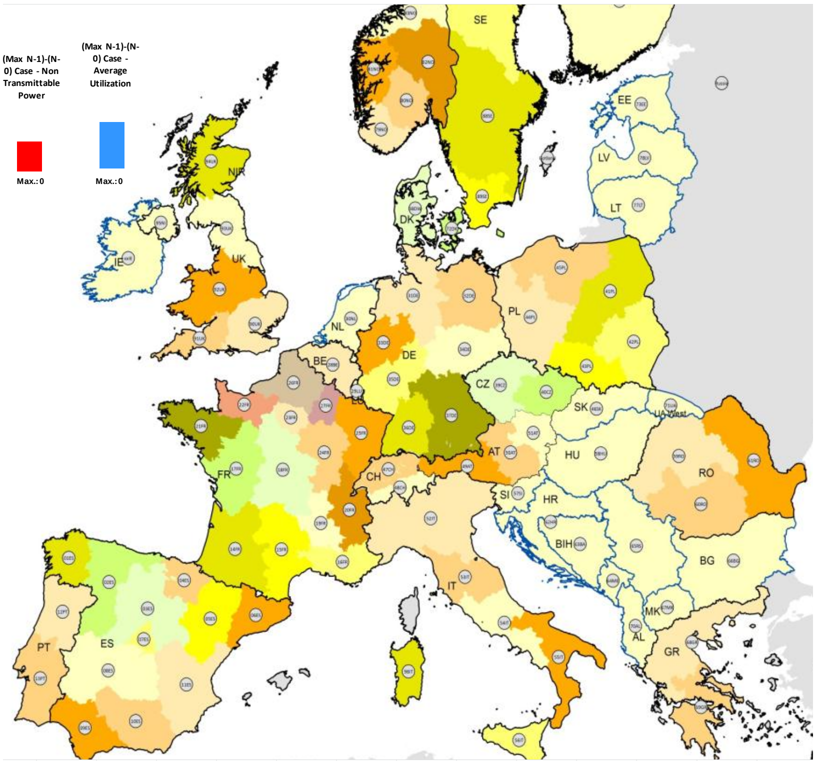

Figure 32: X-16 – Strat 2 – Summer Low

X-16: Small and Local – Strategy 3

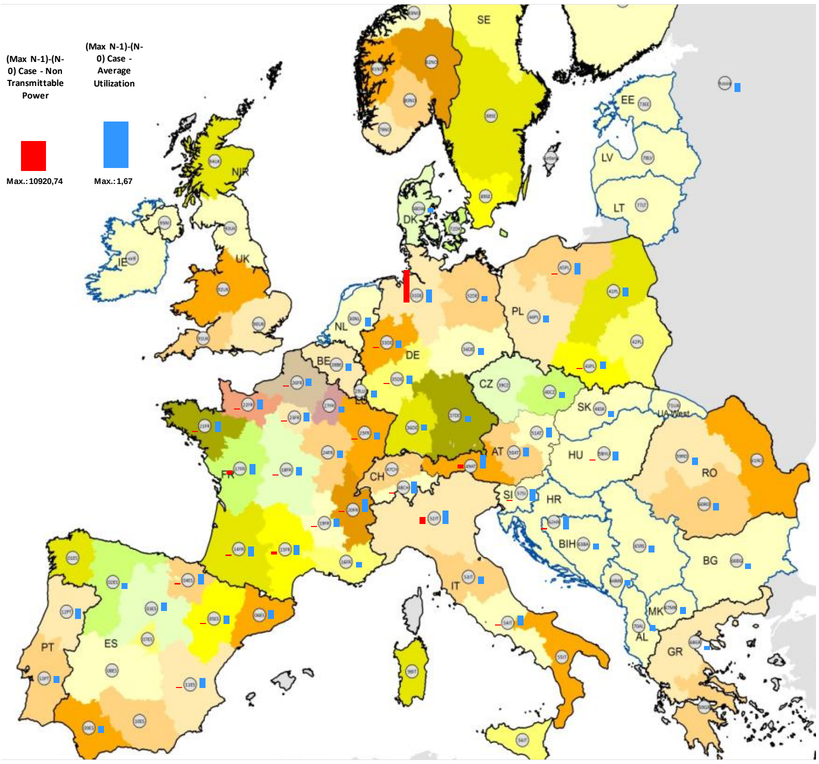

Figure 33: X-16 – Strat 3 – Winter Peak

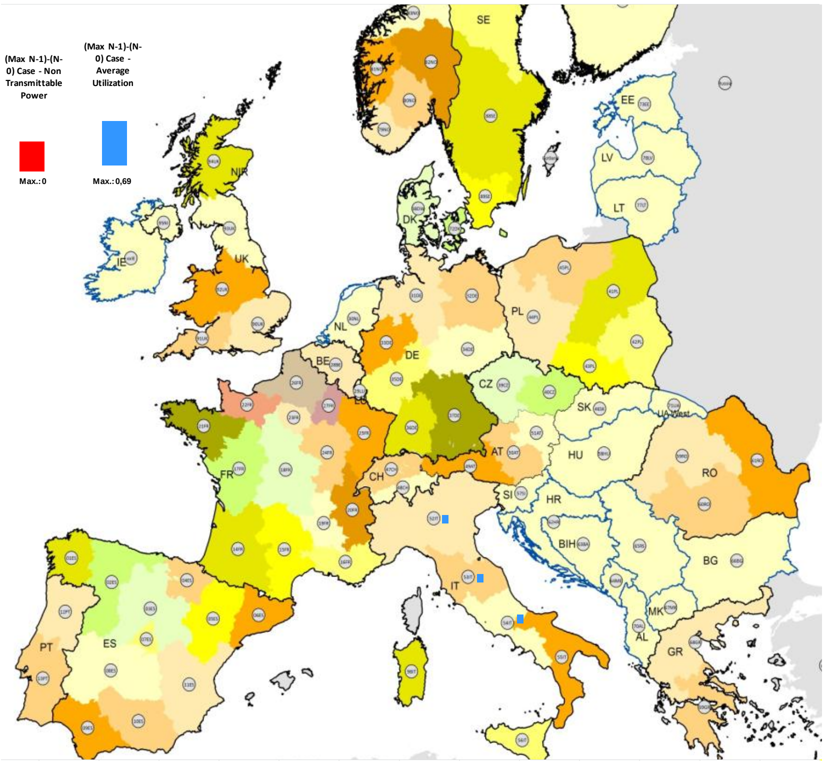

Figure 34: X-16 – Strat 3 – Summer Low