e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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D 8.7	**Recommendations about critical aspects in long-term planning methodologies**		

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Document information

General purpose

This document is the deliverable D8.7 of the e-Highway2050 project. It presents the "Recommendations about critical aspects in long-term planning methodologies". These recommendations are based on the results obtained in the Work Package 8, on the development of an enhanced methodology for long-term planning.

We present these recommendations for each step of the proposed methodology and we split them in three types:

- Improvements of existing tools and methods: they consist of incremental improvements of existing solutions and tools easy to implement, and are generally pre or post processing.
- Specifications for new tools: industrial IT solutions must be developed, however we have a good idea of the specifications for these new tools, thanks to the prototypes developed during the project. There is a moderate risk associated to scalability issues and computation times.
- Recommendations for future research: the needs of the project highlighted some open questions on critical aspects of the problem. We proposed heuristics solutions to these requirements, but a deeper R&D study could be useful to improve them.

Change status

Revision	Date	Changes description	Authors
V1.0		Initial version	P. Panciatici, C. Pache, L. Sigrist, F. Echavarren, S. Lumbreras
V1.1		Updates following review from partners	C. Pache

EXECUTIVE SUMMARY

Long-term transmission planning over large power systems, such as the European transmission network, is a very large and complex problem. Indeed, transmission planning is usually performed for time horizons comprised between 10 and 20 years and current methods have not coped so far with planning over large areas and with increased uncertainty. This is even more the case when integrating significant shares of renewable generation. Today, any national transmission system in Europe is planned using expert judgement. Therefore, Work Package 8 of the e-Highway2050 project aims at defining a new methodology where long-term planning is formalised as an optimisation problem, and at specifying new tools. Advanced optimisation and simulation methods are investigated to tackle this complex highly combinatorial problem, taking into account the stochastic and dynamic behaviours of the system. A Monte-Carlo approach is used to consider the stochastic dimension of the problem. The problem is solved from a transmission system operator (TSO) perspective, with no control over generation planning. Though, several possible evolutions of the electricity sector are investigated for different scenarios. The main challenges arise from the spatial, temporal and stochastic complexities. Thus, methods to reduce the size of the grid or to choose relevant snapshots among the 8760 hours of a year have been developed. The process followed by the developed methodology is represented in Figure 1.

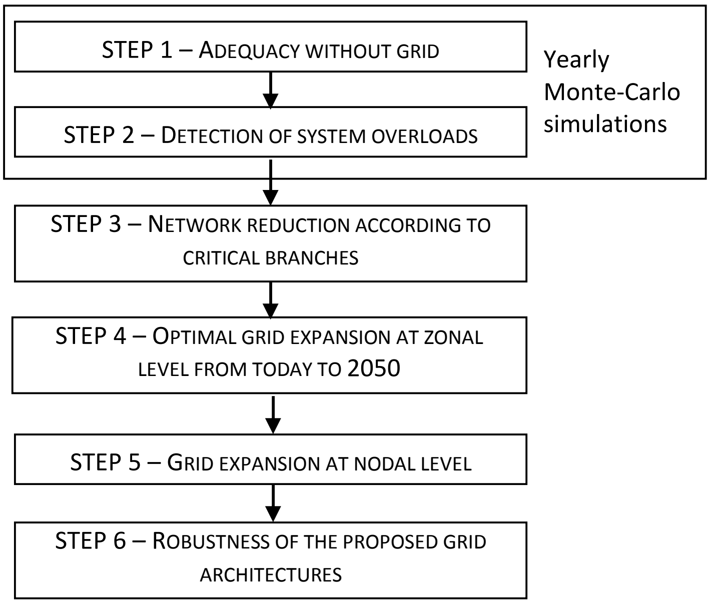

Figure 1 *– Methodology proposed in e-Highway2050, WP8*

In a first step, controllable generation and consumption are calculated with an hourly time step to ensure power adequacy between production and load for each scenario (i.e. generation mix) and time horizon. Grid constraints are not taken into account at this step and several patterns of uncertainties are considered. In a second step, overload problems are detected on a simplified initial pan-European nodal grid (around 1,000 nodes). Then, in a third step, the initial network is reduced according to critical branches, leading to a zonal initial grid (100 zones). In a fourth step, the modular development plan is calculated at the zonal level considering all time horizons and the whole set of scenarios. Starting from the zonal modular development plans, a grid expansion is performed for the first two time horizons at a nodal level. Finally, the robustness of the nodal grid architectures is checked to ensure that these grids can be operated without major voltage or stability issues.

The complete detailed methodology is described in deliverables 8.2 to 8.5, while deliverable 8.6 presents the feasibility of the method through a test case of the size of the European network. The implementation of this approach on a realistic test case confirms that Transmission Expansion Planning (TEP) is a complex problem that calls for optimization techniques, although their application is difficult in real systems.

Long-term planning needs to consider different generation scenarios for the future development of the transmission system. For each long-term scenario, a range of different operation situations (snapshots or short-term uncertainty) should be taken into account. We recommend the use of Stochastic Optimization techniques to consider short-term and long-term uncertainty.

One main feature of the developed methodology is the use of reduction techniques, spatial or temporal, to incorporate the most important features of the problem while keeping it in manageable sizes. For instance, different transmission grid models, from 1000 nodes to 100 zones, are used depending on the complexity of the problem: transmission grid expansion is performed on the zonal network when all the time horizons and scenarios are considered at the same time, while reinforcements are proposed on the nodal grid only for the first time horizons where the development is common to all scenarios. Most of the computation power spent in the method aims at reducing either the size of the network or the number of snapshots and candidates kept in the expansion problems: reduction techniques are a key feature of the developed method. Indeed, applying reduction techniques will, most probably, be necessary to allow planners to incorporate the most important features of the problem while keeping it in manageable sizes.

Different tools and techniques must be combined in order to undertake TEP given the multi-faceted complexity of the problem. Some of them are described below.

Reduction techniques

The problem may be reduced in several ways before being tackled using optimization. Possible approaches include time reduction, stochastic or network reduction. First, the project investigated snapshot selection techniques to reduce temporal and stochastic complexities. Regarding spatial complexity, network reduction techniques have been developed. However, the equivalence between the expansion in the reduced network and the detailed (nodal) network should be further researched. Finally, the set of network reinforcement alternatives to be explored may also be reduced, focusing on the most promising ones and discarding others that do not make sense from a techno-economic point of view. Further research could study the impact of the reduction in a deeper way than the one that could be included in the scope of the project. One important aspect is to find the best trade-off between reduction and accuracy.

Power flow calculation

Using a DCPF seems better suited for TEP. Only approximate calculations for losses can be considered manageable in this context. Developing efficient ACPF solvers is extremely interesting, although their direct incorporation to automatic TEP is difficult. Besides, adequately representing the flow controlling features of new technologies may prove to be very valuable to increase the efficiency of expansion planning solutions computed.

Reliability/Network maintenance

The incorporation of reliability or line maintenance decisions using classical techniques can lead to unmanageably large problems. We recommend the use of simplified, heuristic procedures to this aim whose results can be introduced as constraints in the optimization problem. Further research could lead to more sophisticated, efficient heuristics.

We propose recommendations for each step of the proposed methodology and we split them in three types:

- Improvements of existing tools and methods: they consist of incremental improvements of existing solutions and tools easy to implement, and are generally pre or post processing.
- Specifications for new tools: industrial IT solutions must be developed, however we have a good idea of the specifications for these new tools, thanks to the prototypes developed during the project. There is a moderate risk associated to scalability issues and computation times.
- Recommendations for future research: the needs of the project highlighted some open questions on critical aspects of the problem. We proposed heuristics solutions to these requirements, but a deeper R&D study could be useful to improve them.

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1. Introduction: reminder on the proposed methodology and general recommendations

Long-term transmission planning over large power systems, such as the European transmission network, is a very large and complex problem. Indeed, transmission planning is usually performed for time horizons comprised between 10 and 20 years and current methods have not coped so far with planning over large areas and with increased uncertainty when integrating significant shares of renewable generation. Advanced optimisation and simulation methods are investigated to tackle this complex and highly combinatorial problem, taking into account the stochastic and dynamic behaviours of the system. A Monte-Carlo approach has been used to consider the stochastic dimension of the problem. The problem is solved from a transmission system operator (TSO) perspective, with no control over generation planning. However, several possible evolutions of the electricity sector are investigated for different *scenarios*. The main challenges arise from the spatial, temporal and stochastic complexities. Thus, methods to reduce the size of the grid or to choose relevant snapshots among the 8760 hours of a year have been developed. The process followed by the developed methodology is represented in Figure 2.

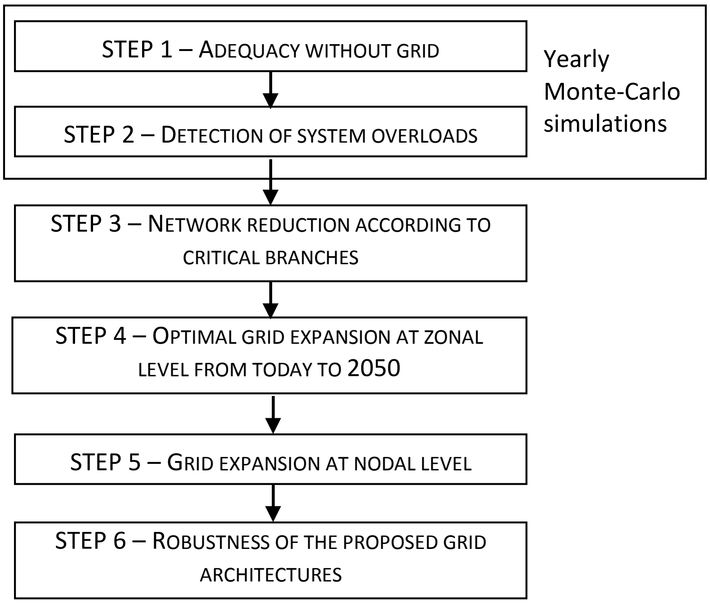

Figure 2 *– Methodology proposed in e-Highway2050, WP8*

In a first step, controllable generation and consumption are calculated with an hourly time step to ensure power adequacy between production and load for each scenario (i.e. generation mix) and time horizon. Grid constraints are not taken into account at this step and several patterns of uncertainties are considered. In a second step, overload problems are detected on a simplified initial pan-European nodal grid (around 1,000 nodes). Then, in a third step, the initial network is reduced according to critical branches, leading to a zonal initial grid (100 nodes). In a fourth step, the modular development plan is calculated at the zonal level considering all time horizons and the whole set of scenarios. Starting from the zonal modular development plans, a grid expansion is performed for the first two time horizons at a nodal level. Finally, the robustness of the nodal grid architectures is checked to ensure that these grids can be operated without major voltage or stability issues.

The implementation of this approach on realistic test case confirms that Transmission Expansion Planning (TEP) is a complex problem that calls for optimization techniques, although their application is difficult in real systems.

Long-term planning needs to consider different generation scenarios for the future development of the transmission system.

For each long-term scenario, a range of different operation situations (snapshots or short-term uncertainty) should be taken into account. The use of Stochastic Optimization techniques is recommended to consider short-term uncertainty.

Applying reduction techniques will, most probably, be necessary to allow planners to incorporate the most important features of the problem while keeping it in manageable sizes.

Different tools and techniques must be combined in order to undertake TEP given the multi-faceted complexity of the problem.

In this document, some more detailed “Recommendations about critical aspects in long-term planning methodologies” are presented. These recommendations are based on the results obtained in the Work Package 8: “Enhanced Pan-European Transmission Planning Methodology”.

2. Recommendations on Step 1: Adequacy without grid

In this first step, balanced time series of consumption and production are calculated. A Monte-Carlo approach has been used to take into account the stochastic dimension of the problem and to study the response of the power system to diverse possible events. Adequacy simulations are performed for each set of stochastic inputs randomly sampled, such as wind or solar production, load, hydro inflows or outage of thermal units.

2.1. Improvement of existing tools and methods

Probabilistic and sequential simulations

Probabilistic simulations are necessary to ensure robustness of the results, especially with high RES penetration. The Monte-Carlo approach is the most suited, and highly recommended in this project. Either in WP2 or in the final test case of WP8, 100 Monte-Carlo years were simulated for each scenario and time horizon. Sensitivity analysis could be carried out to define the optimal number of Monte-Carlo years to simulate.

Sequential simulations are necessary to capture temporal phenomenon like hydro generation or storage. An hourly time step covering one year seems a good trade-off between accuracy and computation time.

Some existing tools, such as the model ANTARES used in WP2/WP4 (see D2.1 "Data sets of scenarios for 2050" [16]), already propose probabilistic and sequential simulations. However, this practice should be further extended and promoted over deterministic approaches.

Modeling of uncertainties

Time series modeling is a thoroughly established subject with many developed methods. In the proposed methodology, time series are decomposed so as to extract their deterministic patterns, namely their trend and their seasonality. The interest of this decomposition is to isolate the random part of the time series from the one which can be logically explained, either by the evolution of the state of the power system or by the intrinsic periodic patterns of the consuming behaviors and climatic conditions. The most popular approaches to identify the trend and seasonality are regressions, while the residual part, also called stochastic component, is commonly represented by *ARMA-type* models, *Markov chains* or *diffusion-type* models. In our case, we want to sample new time series of several phenomena (load, intermittent RES, hydro inflows). With the aim of covering the specificities of each of them, we advise not to settle on just one model. Two models have been retained so as to be able to capture many probability density functions (pdf) and autocorrelation functions:

- *Seasonal ARMA models*, which can easily handle Gaussian processes, are especially adapted to complex temporal autocorrelation structures, such as load time series.
- *Diffusion-type models* are more suitable for non-Gaussian time series. They can generate series with a given common pdf and a simple exponential time decaying autocorrelation, and would be typically applied to uncontrollable RES and inflows time series.

Thus, depending on the intrinsic characteristics of the phenomenon we are dealing with, one approach or the other should be selected.

The issue of spatial correlations between several time series in probabilistic power system studies is raised with the development of RES generation. For instance, a large cloud covering adjacent zones of the system correlates their photovoltaic generation. However, the generation of correlated random variables is a complex mathematical problem. A simpler approach consists in modeling the spatial correlations on the innovations: Gaussian white noises generating the time correlated random time series, instead of considering them on the stochastic components, which are complex stochastic processes. This method, which has been notably applied on the innovations of *ARMA models* by McCormack & al. [10] and Morales & al. [11], was extrapolated to the innovations of *diffusion-type models* in this project. Thus, we propose a method to generate correlated innovations with an empirical computation of the correlation matrix. More details are provided in D8.2 "Enhanced methodology for the computation of demand/generation scenarios" [18].

This method enables to generate robust time series if the historical database only provides a limited number of climate years but a sufficient spatial and temporal resolution. A rigorous modeling of temporal and spatial correlations is crucial in this case. Another solution could be to directly build time series from a large database with enough climate years, such as the one provided by Meteorological Office (e.g. Meteo-France). This subject will be tackled in the part on future research.

Hydro generation

Hydro modeling is a complex issue. We propose to determine the volume targets to be reached at the end of each week, for all the reservoirs of the system, through a yearly adequacy problem decomposed into 52 weekly sub-problems with a rolling-planning of hydro resources. As it is unrealistic to consider full knowledge of the stochastic inputs on a 1-year timeframe, the allocation of the hydro energy is made through an iterative method with a 1-week foresight rolling planning. The hydro schedule is recomputed each week with the real value of the stochastic inputs of the week to come and by assuming an imperfect forecast of the stochastic inputs of the following weeks.

2.2. Specifications for new tools

Maintenance scheduling

Maintenance scheduling refers to the planned shutdown of thermal units, like the ones made for refueling or to perform preventive maintenance operations. In long-term studies, the yearly patterns of residual load can be significantly different than today, thus following the current trends for maintenance scheduling is not relevant. We propose a heuristic which plans maintenance of thermal units considering the excepted residual load, so as to affect security of supply as little as possible. Thus, the maintenance is planned when the expected residual load, equal to the load minus the non-controllable generation, is low. We believe that this mimics realistically implementable maintenance strategies. Even if some countries may already use this kind of approaches, this practice could be generalized.

Demand Side Management

Demand Side Management (DSM) can have a significant impact in long-term scenarios, and it is advised to model it. Taking it into account within the optimization problem is of course better if computation times allow it. DSM has been modeled in our prototype of adequacy simulator: it is possible to shift a part of the load within a given delay time. However, the model we propose should be improved in case of higher participation rates of DSM, and especially its recovery effect. One critical challenge for the modeling of DSM is the lack of information about its real behavior, as it is not yet widespread.

Unit Commitment

A perfect modeling of thermal units can seem quite complex for a study at a pan-European scale. The use of a unit-commitment model with binary variables and time dependent constraints on such a large area indeed implies a longer computation time. A trade-off between accuracy and computation time is necessary. This complexity has already been tackled in the literature and it is also taken into account with ANTARES in WP2 (see D2.1 "Data sets of scenarios for 2050" [16]). In our adequacy model, we used a formulation of the unit-commitment problem proposed by G. Morales-España & al. [12][13] which is tight and compact, and particularly suited for commercial MILP solvers. It offers a unit-commitment model, with a representation of the flexibility of the units via minimum up-down times constraints. Thus, it is possible to improve the efficiency of thermal unit model by taking advantage of MILP solver improvements.

2.3. Future research

Modeling of uncertainties

The demand and RES generation time series have a huge impact on the adequacy results. Accurate modeling is crucial to ensure relevant results; this modeling is based on a learning set of weather conditions. The temporal and spatial correlations are also critical in this case. However, if the database provides enough climatic years, they could be directly converted into RES generation and consumption time series. More research could be done on the comparison of the RES generation of time series from historical data or based on weather scenarios, such as the ones provided by meteorological agencies (e.g. Meteo-France).

Another subject which has not been tackled in the project is the consideration of the climate change not only on the excepted values of weather conditions but also on their seasonality and correlations.

Hydro generation

The modeling of hydro plant becomes more and more important, given that they virtually are the most efficient means for providing storage and flexibility capabilities. Some complex hydro valleys exist in the European system (e.g. Alps) with delayed impacts on run of the river hydro plants. It is intractable to have a detailed modeling of all the European hydro valleys when we want to simulate the full European Electrical system. Generally, equivalent hydro plants and associated equivalent large dams, typically one by country, are considered. These simplifications are performed by experts preserving the energy characteristics but not necessarily the hourly power generations. The approximation errors could be larger than the impact of dispersed storages or DSM on the hourly power balances. Research should be performed to propose a formal approach in order to simplify hydro valleys while preserving more accurately the hourly power generations.

3. Recommendations on Step 2: Detection of system overloads

Once the optimal dispatch of generation has been obtained in a copper-plate approximation for the different Monte-Carlo years, and for each scenario and time horizon, we want to quantify the congestion of transmission lines in the initial grid that would be induced by these injections. This is done by running hourly DC Optimal Power Flows (OPF) which minimize the cost of adjusting controllable generation and load from the optimal dispatch, while complying with network constraints and using in the best way power flow controls (HVDC lines, Phase Shifter Transformers (PST)). This will enable to detect which lines are the most critical for the system across all the Monte-Carlo years, scenarios and time horizons.

3.1. Specifications for new tools

Each hourly DCOPF is modeled as a linear optimization problem and solved independently for each time step. This leads to several millions of DCOPFs to solve (e.g. 3,384,000 in the final test case performed in WP8). In our prototype, we decided to run the DCOPFs in parallel for each year with a hot-start between two successive problems of the same year. Indeed, they are very similar problems: it is efficient to re-use some internal intermediate results (e.g. basis) from one problem to another. However, a trade-off between parallelization and hot-start could be investigated to improve the implementation of large numbers of DCOPFs. For instance, a clustering of similar DCOPF problems could be more efficient than our chronological grouping.

3.2. Future research

Re-dispatch costs

This optimal hourly dispatch returned by the adequacy simulator is performed in a copperplate approximation. This dispatch corresponds to the solution that minimizes overall system cost. Thus, when grid constraints are taken into account this optimal dispatch is unlikely to be feasible, especially in long-term horizons where the network is no longer adapted. Changes in the generation and consumption injections will have to be considered to meet the network constraints. There are two types of changes: increase of generation (resp. decrease of consumption) and decrease of production (resp. increase of load). Each change is associated to an adjustment cost, depending on the hour, the type of the injection and the direction of the change. The distinction between an upward change (increase of injection) and a downward change (decrease of injection) is made. We tried to define a way of calculating these adjustment costs so that they represent the difference between the system operating cost from the reference case, in copperplate approximation, and the one with grid constraints. We based the calculation of these costs on a priority order between the different types of generation and consumption. Further studies would be interesting to assess whether the resulting congestions are well depicted by these costs, especially in the proposed approach where time-dependent constraints are not considered (DCOPFs are solved independently for each time step).

Unit Commitment

In the DC OPF, we want to allow start-up of thermal units which are shut-down in the adequacy simulation, but not under maintenance or in outage. As we want to keep the problem linear, we allow the power production variable to vary continuously within 0 and P^{max}. Thus, the modeling of the unit-commitment has been simplified a lot, and further research should be done on the consideration of start-up cost in the DCOPF problem.

4. Recommendations on Step 3: Network reduction according to critical branches

The initial nodal network (around 1,000 nodes) is reduced to 100 zones. This network reduction is performed according to critical branches, which should minimize the need for internal (intra zonal) reinforcements. Critical lines are either selected using the indicators provided by the DCOPFs, or correspond to power flow control devices (HVDC lines or PST). Once the network partition is obtained, equivalent network characteristics (reactance values and capacities) are computed. This zonal model will constitute the starting point for a modular network development plan.

4.1. Improvement of existing tools and methods

Identification of critical branches

We define the critical branches so that they represent the main features of the grid. They should present a special interest for the purposes of TEP, such as frequent congestions or power flow control (HVDC lines or PSTs). In this respect, we scroll through all the simulated DCOPFs, i.e. all the scenarios, time horizons and Monte-Carlo years, to compute congestion indicators for each line. This approach is easy to implement as post-processing of existing tools and would help detect which lines should be given more attention. The only critical issue with this method is the need for detailed data and assumptions over the European simplified model (1,000 nodes) to be able to run the DCOPFs.

Network reduction

We propose a network reduction method which keeps the identified critical branches in the reduced model. This approach aims at minimizing the need for internal reinforcements. In order to do so, we implemented a modified version of the *k*-means clustering algorithm, with an initial partition of the network which splits it so that end nodes of critical branches are in different zones. This initial partition is smarter than a random initialization of the *k*-means algorithm, and helps find a stable clustering more easily.

4.2. Future research

Identification of critical branches

Different criteria for the identification of critical branches were studied in WP8:

- The average flow relative to the maximum capacity of a line, which captures concisely the utilization of a transmission line,
- The proportion of operation hours where the line is congested,
- The value of the dual variable of the capacity limit constraints of the DCOPF,
- The difference between the nodal prices at the receiving and ending sides of the line weighted by line flow.

The results obtained on the test case were in favor of the average flow criteria. However, further studies should be done on other criteria or on the selection threshold for each criterion (e.g. average flow above 60% of the maximum capacity of the line). The same remark can be made on the tuning of some of the network partition parameters, such as the distance calculation between nodes in the clustering. We decided to use a composite distance, half electrical distance and half geographical distance, but further sensitivity studies could be performed on this choice.

Equivalent capacity calculation

This is a very difficult problem with a lack of references on the subject. We have proposed a method to compute equivalent capacities, so that capacities of the inter-zonal corridors should permit all the inter-zonal flows that may occur in the nodal network. The proposed approach is one alternative among others that is suitable for the requirements of the overall methodology. For instance, it has been chosen to ensure N-1 system reliability at the nodal expansion, thus it is not considered in the former steps.

However, there is no clue today on which of the existing methods is the most relevant. The lack of references proves that more research should be conducted on this subject.

5. Recommendations on Step 4: Optimal grid expansion at zonal level from today to 2050

The purpose of Transmission Expansion Planning (TEP) is to provide grid expansion candidates that will allow the grid to take advantage of most of the generating units while reducing load curtailments at a minimum investment cost. It is a trade-off between minimizing the investment costs and minimizing the generation and load curtailment costs. Before optimizing the TEP, two components must be defined: the candidates in which the model is allowed to invest and the snapshots on which the impacts on system operation are assessed.

5.1. Step 4.1: Snapshot selection

5.1.1. Improvement of existing tools and methods

Snapshot selection is necessary to make the problem manageable by humans or even computers. In today grid expansion studies, snapshots are defined manually and usually describe worst case scenarios such as peak and off-peak hours. Improved snapshot selection could be implemented easily to help the planner. In WP2, snapshots have been selected by expert choice based on the comparison between copperplate and starting grid simulations (DCOPFs). They are used to identify candidates, and thus they focus on high energy not served, spillage or re-dispatch (see D2.3 "System simulations analysis and overlay grid development" [17]).

5.1.2. Specifications for new tools

We propose an automatic method to select snapshots based on a clustering algorithm using information from hourly DCOPFs for all scenarios and horizons. As snapshots are used both to identify candidates and in the TEP optimization, they should be representative of all the situations. We used a version of the *k*-medoids algorithm (*CLARA, Clustering for Large Applications*) to be able to cluster such large data sets in a reasonable time. However, more effort could still be done on a more efficient implementation of the clustering algorithm, such as testing different languages (*R* or new data mining languages) or other algorithms (such as *CLARANS, Clustering Algorithm Based on Randomized Search*) A smarter initialization method than a random one, could also be investigated.

5.1.3. Future research

Snapshot selection criteria

In deliverable 8.4a ("Enhanced methodology to define the optimal modular plan to reach 2050 grid architectures" [19]), we studied 3 different selection criteria for the snapshot clustering: one based on zonal price differences (congestion related), another on non-controllable production and consumption (balance related), and a hybrid one. The expansion results obtained on a small test case (Garver system) with selected snapshots based on these 3 features were in favor of the zonal price differences. Thus, this criterion has been kept to select representative snapshots in the final test case (European size). However, sensitivity studies on the impact of other snapshot selection criteria on the TEP results should be conducted on a larger network to assess whether or not using zonal price differences is relevant or if other criteria would be better.

Number of representative snapshots

Another subject to be studied is the minimal number of representative snapshots that would be needed to obtain a stable zonal expansion (that is, a zonal plan that would not change notably if more snapshots were included). In the test case, we only kept 5 snapshots to represent 100 years. Indeed, we had to find a trade-off between the number of snapshots and the computation time of the TEP. Improvements in the TEP (tackled in Section 5.3) will enable the use of more snapshots, thus it will be useful to know the minimum number of snapshots leading to a stable expansion solution. A possible way of carrying this study without running the actual TEP optimization would be to perform this assessment on the simplified relaxed version of the TEP already used for candidate selection. This requires a coupling between snapshots and candidates selection.

5.2. Step 4.2: Candidate selection

It is highly advisable to use automatic candidate discovery methods for the selection of the lines that will be considered in the optimization. The expert approach can miss candidates whereas an automatic selection is more exhaustive.

5.2.1. Improvement of existing tools and methods

A post-processing of simulation results (DCOPFs) to assess the profitability of candidates can be easily implemented. Simulation results can be used in a first step. We calculate the profitability of a candidate as the ratio between its potential benefit (based on the price difference between the two connected zones and the maximum potential flow on the candidate) and the annualized investment cost. This can give to the planner an evaluation of the profitability of a candidate by directly using simulation tool outputs. In a second step, it could be interesting to run a relaxed TEP with these profitable candidates to find which of them would be installed. This can be a specification for new tools as well.

5.2.2. Specifications for new tools

It would be interesting to include GIS-data in the candidate selection process. This is more important in a context that considers long-range transmission lines. This remained outside of the scope of the project.

5.2.3. Future research

Several candidate technologies could be investigated in the candidate selection process, such as hybrid candidates, the switch from AC to DC lines or PST (Phase Shifting Transformers), which can be more cost-efficient than transmission lines in certain situations and could therefore be considered as candidate investments as well.

Finally, the use of PST to balance the flows in parallel lines should be studied. Indeed, in the case where a candidate is installed in parallel to an existing line, there may be some congestion issues in one of the parallel lines leading to a sub-optimal use of the grid. PSTs could be helpful in these situations.

5.3. Step 4.3: Transmission expansion planning optimization at zonal level

All scenarios and time horizons are considered at once in the TEP, ensuring consistency between short-term and long-term reinforcements, and common corridors for the first 10 years.

5.3.1. Specifications for new tools

By testing different options of the MILP solvers, we were able to improve the TEP performance. Thus, a benchmark should be continued on modelers and MILP solvers to increase the TEP efficiency. This would enable to use more snapshots and candidates in the TEP optimization.

As it has already been said for the unit-commitment problem, the modeling of the TEP should be adapted so that it could take advantage of MILP solver improvements. We modified the formulation of the two-level TEP problem through a "disjunctive model" [14] so that the optimization can be written as a Mixed Integer Linear Programming problem.

5.3.2. Future research

We decided to minimize the sum of investment and operational costs in the objective function; however other objective functions, such as least-regret, could be studied. This could also improve the scaling of the problem which is not very good in our formulation of the TEP.

6. Recommendations on Step 5: Grid expansion at nodal level

Nodal simulations make sense only for short-term studies. Uncertainties are too high in long-term studies, and only explanatory studies can be performed. We suggest an approach to go from zonal to nodal level ensuring that the zonal capacities obtained while considering long-term issues are fulfilled.

6.1. Specifications for new tools

Phase Shifter Transformers (PST) could be associated with new or existing power lines as candidate investment. This should allow finding a better balance of the flows between parallel corridors with different technology. The optimization must take into account the flexibility offered by these PSTs.

An N-1 criterion has been implemented only for the candidate definition using a rule of thumb to increase the capacity. A better incorporation of reliability constraints in the problem is possible with a heuristic procedure.

6.2. Future research

One limitation of the proposed approach is due to the usage of a linearized model of the grid (DC approximation), without taking into account impact of losses and MVar investments in expansion decisions. AC models lead to non convex optimization problem even with relaxed integer variables. Finding feasible solutions of the TEP is very challenging because this requires finding the global optimal solution of ACOPF. New ideas have been recently proposed to find a global optimum using convex relaxations of ACOPF (SDP). The scalability of this type of approaches is still not guaranteed but they are very promising and could bring the ultimate solution.

The reliability criteria must be revisited and the traditional N-1 seems less and less relevant in the context with a large share of intermittent generations. Good practices should be integrated in formal risk based framework. For instance, in the case of the connection of wind farms, wind power curtailment could be used as a solution in case of very low probability events combining a line failure and a high wind speed, instead of building oversized power lines complying with the standard N-1 criteria. The ongoing European project "GARPUR" will propose new reliability criteria which should be included in any expansion planning.

Taking advantage of all the possible flexibility (PST, HVDC links embed in AC grid, DLR, …) is also a challenge at the planning stage, we have to pay attention to design a repairable grid keeping the minimal required redundancy.

We have proposed a very simple and easy to understand mean to consider the results of the zonal transmission expansion planning in the nodal TEP (the obtained inter-zonal capacities are set as constraint in the nodal expansion) but better solutions could be investigated.

Another important recommendation is to develop indices and post processing tools to understand and explain the solution provided by the optimization problem: it is important to grasp the purpose of each investment. This recommendation is also applicable to the zonal expansion. With the objective of making the transmission expansion planning more transparent, it will be also very interesting to study the relationships between investments (alternative, complementary) [15].

7. Recommendations on Step 6: Robustness of the proposed architectures

7.1. Step 6.1: Methods and tools for steady-state analysis

The aim of the set of steady state analysis tools is to build a valid full AC network model using the information obtained from the linearized DC power flow.

The first step is the DC-to-AC process, where the missing reactive power information of the network is estimated using standard values, and possible parameters unacceptable in an actual AC network are detected and corrected. Once the preliminary version of the AC model has been built, it is to be expected that power flow will diverge. Thus, a tool is required to achieve convergence by balancing the reactive power using shunt elements. Once convergence is reached, the reactive power dispatch is optimized by controlling reactive power generation limits and bus voltages, using both shunt elements and voltage of generation units. Finally a load margin to voltages collapse computation algorithm has been included to check the robustness of the scenario.

7.1.1. Improvement of existing tools and methods

The DC-to-AC procedure has to deal with some issues that are acceptable in a simplified DC model, but can lead to the divergence of the power flow in a full AC model.

Active power system balance

Power balance is a key variable to guarantee the convergence of the power flow. The sum of active power production has to be equal to the demand plus the active power losses. Once the power flow is run, all the power gap between the generation and the demand plus active power losses, goes to the generation units of the slack bus. In case the unbalance is too large, the power flows around the slack bus can be higher than what the network can handle.

A great unbalance between power generation and demand will lead on to divergent power flow. Therefore, an active power generation redispatch is highly recommendable to avoid that the slack bus presents a large production (or absorption). The criteria to apply the redispatch may vary, but it is usually defined as proportional to the initial production of each generation unit.

Active power system inter-zone balance

The inter-zone power exchanges are defined by the difference between the generation and the demand in the zone (the zone is a set of nodes). When the zone presents connectivity with more than one other zone, then the inter-zone power exchanges will also depend on the power balances of the rest of the zones.

Great unbalance between interconnected zones may not only complicate the convergence, but also the final case scenario will probably present unrealistic inter-zone power transfers. Therefore, an active power generation redispatch is recommendable to improve convergence and avoid unrealistic inter-zone power transfers.

Lines parameters

When using network planning on reduced networks, some lines can be defined using unrealistic parameters. Since planning algorithms use the linearized DC approximation of power flow problem, those unrealistic lines can be managed without having numeric problems. However, in the full AC power flow model, the equations are non-linear and the presence of unrealistic parameterized lines may lead to power flow divergence. Most common unrealistic parameters are related to the length of the lines.

In the case of low impedance lines (typically z<1.0e-4 pu, equivalent to 500 m of a 380 kV line), this magnitude introduces large elements in the admittance matrix and also in the Jacobian matrix of the power flow equations. That numerical perturbation reduces the condition number of the Jacobian matrix which lowers the chances for power flow convergence. If there are low impedance lines in the network, it is recommended to group all the interconnected buses with low impedance lines and consider them as one single bus.

High impedance lines (typically >2.0e-1 pu, equivalent to 1000 km of a 380 kV line) add noise to the power flow solution, due to the fact that larger impedances force the system to consider large voltage drops if power flows through them. If there are high impedance lines in the network, it is recommended to keep them in the system, but considering them opened.

Islands detection

The topology of the network may present one or more disconnected buses, i.e. they are not connected (directly or indirectly) to the slack bus of the system. Therefore, the power flow cannot be solved since the isolated buses need a slack bus to keep the system balanced. As a consequence, it is usual to set the islanded buses as “isolated” and disconnect every device (lines, generation units, loads, etc.) which belongs to the islanded buses.

Load power factor adjustment

When the reactive power demand information is not available, the selection of the load power factor is critical. A high inductive power factor for the system loads may lead to an unsolvable case scenario if the system reactive power resources cannot support that high reactive power demand [1]. A large reactive power demand implies higher power flows through lines, transformers and low bus voltages. In addition, solvability of power flow equations gets worse when generation units saturate their reactive power production limits.

System statistics show loads with power factors more inductive than 0.9, but there are also loads that have power factors close to 1.0, or even capacitive power factors. For the whole system, the mean power factor is usually higher than 0.95. Therefore it is recommendable to choose a realistic power factor for loads, i.e. 0.95 at minimum.

7.1.2. Specifications for new tools

The full AC base case built from the simplified DC model information presents an initial flat reactive power profile. In addition to the possibility of power flow divergence, in the cases where the base case converges, the voltages profile and reactive power flows are usually unacceptable. Thus, a tool is required to ensure the scenario resolving and provide optimized voltages profile and reactive power flows.

Power flow solving

The tool which enables to solve a power flow with unacceptable voltage profiles or reactive power flows employs shunt devices to be placed in the buses with the largest reactive power mismatches. The procedure detects the largest mismatch and places shunt element there.

Shunt placement and modulation can be globally optimized by considering the entire mismatch vector. Formulating this solving issue as an optimization problem [2], in combination with the Lagrange multipliers, a more precise shunt placement and modulation may be achieved, e.g. if a LP optimization problem is formulated and solved considering the solvability restoration plus reactive power management constraints.

QV profile optimization

A QV profile optimization tool employs shunt devices and voltages of generation units to optimize the QV profile of the network. The objective is to improve the reactive power margin of generation units and maintain bus voltages into limits.

Both algorithms employ gradient vector to minimize the corresponding squared violations (reactive power limits or bus voltage). Although the presented results illustrate the performance of that strategy, more effective solutions may be taken, such as quadratic sequential programming [3], where the optimization problem is solved by successive solutions of QP problems where additional constraints may be included to manage the reactive power resources in the network.

7.1.3. Future research

N-1 security analysis

Contingency analysis is one of the most important tasks encountered by the planning and operation engineers of bulk power system. Its purpose is to analyze the power system in order to identify the overloads and problems that can occur due to the outage of one or more elements in the network, such as power lines, transformers or generating units.

A simplified contingency analysis can be run using the linearized DC approximation of power flow problem. Nevertheless, those results may be inaccurate when the full AC network is considered. The DC model only considers active power flows, thus voltage limit checking is not available. Besides, considering only active power flows, some overloads may be undetected because they are due to their corresponding reactive power flows. As a consequence, a full AC contingency analysis is highly recommendable to analyze and report lists of contingencies and associated violations.

Preventive control actions (active power re-dispatch) to solve overloads in base case and in N-1 situation

After a full AC contingency analysis which reports the violations associated to contingencies, control actions may be taken into account to eliminate them. Two strategies are usually considered: corrective and preventive [4]. The corrective strategy establishes the control actions needed after the outage occurs, whereas the preventive strategy considers the control actions adjustment to perform in the base case, so that the system would have no problem after the outage occurs. Therefore, preventive strategy guarantees the security of the system, both in the base case and after some disturbances. Since the built scenarios are going to be the base of future planning, a preventive re-dispatch algorithm will be useful to guarantee the security of the system.

Corrective control actions (active power re-dispatch, even load shedding) to increase load margin to voltages collapse

Load margin to voltages collapse is a useful index to assess the robustness of the system. This index allows the TSO to check if the demand evolution can be a problem for the stability of the system.

In power system operation planning studies, the TSO analyzes the forecasted state of the power system and performs in advance appropriate control actions to fulfill the security criteria [5]. These control actions consist of voltage control resources adjustment (transformer taps, shunts reactors and generation bus voltages) and modification of the generation dispatch (increase and decrease of generation in several units, and connection of off-line ones). Moreover, when the power system is getting close to the load margin, the available control actions may have been exhausted or there may not be fast enough to prevent the system voltage collapse. Therefore emergency load shedding measures may be required [6]. However, it must be considered as a last resort, so demand reduction must be minimized (load shedding in the importing areas and an equal amount of generation reduction in the exporting areas).

7.2. Step 6.2: Methods and tools for transient stability analysis

The set of tools for transient stability analysis developed during the project comprises a tool to build a dynamic model of the power system and a tool to assess transient stability.

Prior to assessing transient stability, a dynamic model of the power system must be built. A tool has been developed for this purpose. It retrieves generator data from a solved AC load flow file and creates the dynamic data file, containing the parameters of the models of generators and other dynamic equipment. Since detailed model parameters of all generators are usually not known a priori, generators are grouped according to six typical generation technologies and each technology is described by an existing reference plant with its standardized dynamic models and model parameters.

The tool to assess transient stability essentially determines the critical clearing times (CCTs) of all possible solid three-phase transmission system faults in an iterative way. In every iteration, the power system response to a particular fault and fault endurance is simulated with PSS/E.

7.2.1. Improvement of existing tools and methods

Data issue

A major problem is the accuracy of data of the models of generators and other dynamic equipment. Actually, the output of the transient stability assessment tool is only as realistic as its input data is. Ideally, data of the dynamic model of all elements is available; however this is usually not the case due to several reasons such as confidentiality, inexistence of validated models, etc.

In [7], an approach to build a system-wide model for the analysis of transient stability and inter-area oscillations has been proposed, where for each generating unit the same standard dynamic models are used. Only generating units with a capacity larger than 250 MW are considered. The remaining units are modeled as constant impedances. However, certain model parameters such as the inertia, the droop, excitation system and PSS gain have been additionally adjusted to fit system-wide measurements.

The developed approach for the robustness analysis classifies generating units according to six generation technologies which are described by an existing reference plant with its own standard dynamic models. Such an extension of the previously described approach is mentioned in [7].

Critical clearing time evaluation

A second, minor problem was to determine transient stability of a large power system. Transient stability has been quantified by means of CCT. Software packages such as PSS/E allow simulating a particular fault; the simulation of a series of faults however requires a specific tool, making use of PSS/E's working environment. The tools allow to simulate all possible solid three-phase bus faults and to quantify the CCT of each of them sequentially. Rather than increasing the endurance of the fault uniformly, a variable increment of the fault endurance has been developed and employed to reduce computation effort.

7.2.2. Specifications for new tools

The problem of data accuracy for models can be theoretically solved if enough measurements are available. No further methods are needed since appropriate system identification techniques already exist to fit the response of standard dynamic models to measurements.

The current tool only considers two-terminal HVDC links, which is reasonable for the considered horizon of the robustness analysis (2020 to 2025). However, in the light of horizon of 2050, multi-terminal HVDC systems (MTDCs) need to be considered as well. Appropriate, standardized models are needed.

Protection models

The current tool does not include protection models such as generator protection, AC and DC transmission line protection, or system-wide protections like load shedding or automatic generation tripping, etc. System-wide and component protections clearly influence the outcome of transient stability assessment. They will also influence the results obtained when assessing the impact of RES and HVDC on transient stability. Most software packages such PSS/E offer a wide range of standard protection models. However, it is crucial to decide which protections and for which components protections are modeled. According to the philosophy of [7], where a system-wide model has been specifically developed to study transient stability and inter-zone oscillations, not every model is able to reflect all dynamics in a manageable computation time.

Faults analysis

The tool to assess transient stability has been applied to solid three-phase bus faults. Although the tool is readily able to analyze line faults, CCT corresponding to line faults have not been studied in the case of reduced system models. Other types of balanced faults such as generation outages, line faults, etc. should be included in the tool. Unbalanced faults can only be simulated in an approximate manner, since PSS/E only deals with positive sequence models.

7.2.3. Future research

Refinement of dynamic models

The current version of the tool considers six typical generation technologies which are described by an existing reference plant with its own standard dynamic models. Although it is reasonable to assume a reference plant, there are differences among generating units belonging to the same technology. A further refinement based on known parameters such as the nominal plant power might be needed. Clustering techniques and decision trees are appropriate methods for this purpose. In addition and as done in [7], it might be necessary to fine tune certain parameters to properly match system responses. Ideally, measurement of plant responses is available for this purpose.

Similarly, models of recent technologies such as VSC-HVDC links still need to be validated with field test measurements. MTDC system models have been developed for many software packages, but they also lack of validation.

Control and protection of HVDC links

Control and protection of HVDC links need to be further addressed. Currently, two fundamental methods exist and are applied to improve transient stability by adjusting DC power set point of the HVDC link: DC power modulation and fast DC power ramping. However, reactive power set points of the VSC HVDC links could also be adjusted in a similar way as DC power modulation. Furthermore, the way reactive power is locally controlled (i.e., constant power factor or AC voltage control) significantly affects transient stability [8].

An additional option for future research in controlling HVDC links is the analysis of re-scheduling of DC power flows among remaining HVDC links when a particular HVDC loses a pole or even trips. First encouraging results have been obtained in [9].

Finally, the impact of current limitations of HVDC links on transient stability need to be further analyzed. For other converter-connected generation sources such as wind power generation reactive power is prioritized over active power during low voltage conditions. During short circuits voltages depress, active power injections of these sources are reduced accordingly, which might favor or not transient stability. The negative impact of active power reduction of HVDC links when currents hit their limits has been shown for a simple system in [8].

7.3. Step 6.3: Methods and tools for small signal stability analysis

The set of tools for small signal stability analysis comprises a Matlab-based tool to assess small signal stability (Small Signal Stability Toolbox - SSST) and a tool to translate the PSS/E data format into the SSST format.

Prior to assessing small signal stability, the PSS/E data format needs to be translated into the SSST format. A tool has been developed for this purpose.

The tool to assess small signal stability has been essentially used to determine the eigenvalues of the power system. Linearized versions of the non-linear models of the dynamic equipment are derived. For smaller systems, the QR method can be directly used. For very large power systems, the tool includes selective modal analysis and the modified Arnoldi method.

7.3.1. Improvement of existing tools and methods

Software packages such as PSS/E provide additional modules to evaluate small signal stability of a power system. NEVA is such a module, offering QR method and selective modal analysis. However, NEVA is only able to analyze some of the PSS/E dynamic library models. VSC HVDC links or wind power generation models cannot be analyzed. Furthermore, user defined models are not supported either. SSST fills in this gap for being a MATLAB-based, easily modifiable code.

7.3.2. Specifications for new tools

The current tool is able to analyze typical models of dynamic equipment, including the six identified conventional generation technologies, most common FACTS devices, and user-written wind generation and HVDC models. It might be necessary to extend this current library for detailed wind power generation models.

Similarly, the current tool needs to be extended to MTDC systems.

7.3.3. Future research

SSST has been used to determine the eigenvalues of the power system under study.

SSST includes tools to analyze eigenvalue sensitivities of certain control devices such as PSS. Eigenvalue sensitivities can be readily employed to validate existing settings of the control parameters of the stabilizers of HVDC links. It can be further used to adjust these settings such that a specific target (certain degree of damping) is achieved. The adjustment must be robust in the sense that it provides satisfactory results under different operating conditions. Finally and in the light of the 2050 horizon and the possible existence of MTDC, the coordinated and robust design of the stabilizers at each HVDC terminal needs to be considered.

8. Recommendations on the "Implementation of the whole methodology"

During the project, we did not explain the interaction between this new type of tools based on optimization and the planners. The assumption is that the role of the planners changes. In the proposed approach, they select the required inputs and the parameters of the method and not any more to manually select which corridors to upgrade, by how much and when. Planners are of course responsible of the "best" expansion planning by selecting the right inputs and parameters of the method, based on their knowledge of the method and perhaps by performing iterations.

We should propose a methodology to tune all the required parameters of the method (clustering…). One important aspect is to find the best trade-off between accuracy and computation time. The available computational power could impact this trade-off.

One very important aspect is how to present the large amount of results to the planners; we should develop some dedicated post processing tools to facilitate their interaction with the advanced proposed method.

We should develop training tools to speed up the acquisition of the knowledge of the method by the planners.

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