Flexplan

Advanced methodology and tools taking advantage of storage and FLEXibility in transmission and distribution grid PLANning

# FINAL SUMMARY OF PROJECT ACTIVITIES, CONCLUSIONS AND RECOMMENDATIONS

D8.2

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# TABLE OF CONTENTS

# KEY FINDINGS

## TRANSMISSION AND DISTRIBUTION GRID PLANNING GUIDELINES

- In the last years, most flexible resources have been connected to distribution grids. Some of them could also be suitable to provide services to transmission. Therefore, whereas a complete integration of TSO and DSO planning studies is out of scope because it would result in a too big system impossible to solve with current hardware and software constraints. Additionally, each system operator would not be authorized to exchange private data regarding its control area with other system operators. However, **TSO and DSO grid planning procedures could be indeed coordinated**. The innovative T&D decomposition methodology proposed by FlexPlan could be a starting point to reflect on possible ways to implement TSO-DSO planning coordination.

- In the future, flexibility elements (storage devices and flexibilization of loads) will become fully fledged candidates for planning, as requested by Directive (EU) 2019/944 (Art. 32, Art. 40) and Regulation (EU) 2022/869 (Art. 13). Flexibility will prove synergic to developing new lines or reinforcing existing ones, as proved by the results of the 6 regional cases developed by FlexPlan. This will increase a lot the number of candidates to be evaluated in grid planning studies.

- Any traditional grid planning methodology based on with-and-without approach (TOOT or PINT, as denominated by ENTSO-E) could prove too sub-optimum, especially in presence of a high number of candidates, for the evaluation of which a huge number of simulations would be necessary. **A new procedure should be put in place allowing the co-evaluation of all candidates**. By running the 6 regional cases, the FlexPlan project has proved the applicability of such approach to planning models having the same size as those used by the system operators.

- **In the future, planning studies should be carried out not for a single horizon year but over several decades in order to design the complete decarbonization pathway from mid- to long-term (2030, 2040, 2050)**. To avoid getting sub-optimal results, privileging mid- over long-term goals or vice versa, the optimization should be carried out in a coordinated way between the different decades, as proposed by the FlexPlan project.

- **Grid planning studies should consider different climate variants weighed each with its relevant probability**. This requires to solve a probabilistic optimization model, as proposed by FlexPlan.

- **Environmental criteria (air quality and carbon footprint) can be successfully monetized and included into the target function used for carrying out planning studies**. FlexPlan has shown this can be accomplished while retaining a linear model, which ensures the numerical tractability of the model.

- FlexPlan has demonstrated that the big dimensionality of the model obtained by implementing all features above can be treated by means **of decomposition techniques (Benders's decomposition, T&D decomposition)**. In this way, provided the implementation is such in a way to allow parallelization by distributing the different optimization processes on several PCs, the calculation time can be kept under control.

# REGULATORY GUIDELINES

- Investments in storage and flexibility will remain mostly in the hands of private investors. **National Regulatory Authorities should translate the suitability of deploying new storage or flexibility in strategic network locations into opportune incentivization tools for potential investors.** This complicates the traditional scheme, where System Operators after carrying out planning analyses were the only subject entitled to invest.

- Such incentivization tools should contain a locational element able to drive potential investors to prefer an investment in critical nodes, identified on the basis of the studies led by the System Operators. **This could be carried out by means of locational capacity markets.** However, the development of a long-term incentivizing framework able to attract investments towards critical locations could reveal regions with high potential for the exercise of market power. In these cases, **market-based mechanisms for the procurement of flexibility services should be combined with long-term contracts with a pre-established strike price**, so as to disincentivize investors receiving long-term incentivisation to apply significant bid-up strategies. In alternative, **a cap on bid prices** could be explicitly established. Finally, a **"must-run" situation**, in which the SO bids the asset on behalf of the owner can also be acceptable, but just in extreme cases.

- **Real time market should be reformed by defining products that allow "flexibility" providers to compete with traditional resources on a "level playing field" basis.** Of course, SO needs should be taken into account too, as buyers of these services. Operative constrains of storage and demand side management should be fully considered.

- Despite some significant yet incremental steps done in 2019/944 Directive, **active use of Demand Response has been inhibited due to lack of a comprehensive regulatory framework for the subject**. In that sense it is difficult to underestimate the importance of the forthcoming Network Code for Demand Response. The FlexPlan Consortium acknowledges the significance of the presented ACER's Framework Guideline for the Code, which presents an outline for the main subjects to be stipulated. The final document shows a great improvement after the public consultation accomplished in autumn 2022. It also creates a logical connection between network development planning as described in Arti. 32 and demand response, as an alternative to system expansion.

- Despite recognising the importance of aggregation for demand response, Directive 2019/944 failed to define role and responsibilities of the Aggregator, the key element in the puzzle, by deferring this task to the National Regulatory Authorities. By contrast, we believe that **role and responsibilities of the aggregators should be accurately designed at a common European level**. In the final version of the Framework Guideline more details have been specified, but the role of Aggregator still remains somewhat unclear and probably has to be properly addressed at another legal level (e.g. in a new version of the 2019/944 Directive). Here, the FlexPlan consortium assumes that an aggregator should act by compensating positions with opposite risk exposures, thus favouring real-time markets operation. However, the business case of the aggregators must also be considered so that their operation is capable to provide them with the needed revenues, without which no real subject, even in presence of a specific regulation, will ever volunteer to take such responsibility.

- **In future energy systems, TSO and DSOs should coordinate their planning activities**. In fact, most of the potentially flexible loads as well as most distributed generation are being connected to distribution systems. However, it is not thinkable to allow a really integrated planning of transmission and distribution: on one side the optimization problem would be too complex and on the other system operators are not allowed to exchange private data with other subjects, be they even other system operators. Therefore, a coordinated approach can be suggested in which by means of an exchange of data at the border between different systems, DSOs can, in case advantageous for the system, oversize their network so as to get fit to provide services to transmission. The T&D decomposition approach proposed by FlexPlan can be, in our opinion, a good starting point for reasoning on this approach.

- Cost-benefit analysis must take into account positive effects of flexibility resources. Key importance must be attributed to GHG and other pollutant reduction. **Environmental aspects should be put in monetary terms so that they can be co-evaluated with more traditional ones (social welfare, etc)**.

- **Market reforms are now investigated in Europe, so as to decouple market prices from gas prices (possibility of price-caps or two-stage markets). These reforms, while considering the role of generators and loads, usually don't consider explicitly the role of flexible resources (e.g. arbitrage between market prices at different times)**. Taking into account the fact that storage and DSM will be two major players in the future provision of ancillary services, a clarification on the nature of the service provided by these subjects would bring to more forward-looking reform of market mechanisms.

# EXECUTIVE SUMMARY

This report provides a synthetic overview of the activities carried out by the FlexPlan project (https://flexplan-project.eu/), which established an innovative grid-planning methodology considering the opportunity to introduce new storage and load flexibility resources in electricity T&D grids as an alternative to building new grid elements. FlexPlan created a new innovative grid-planning tool whose ambition was to go beyond the state of the art of planning methodologies by including the following innovative features: integrated transmission distribution planning, environmental analysis, probabilistic contingency methodologies (in replacement of the N-1 criterion) as well as optimal planning decision over several decades. The new tool was used to analyse six regional cases covering nearly the whole European continent (Iberian Peninsula; France and Benelux; Germany, Switzerland and Austria; Italy; Balkan Countries; and Nordic Countries). These regional cases are aimed at demonstrating the application of the tool in real scenarios as well as at casting a view on grid planning in Europe till 2050. A regulatory analysis completed the FlexPlan activities. Here, barriers and enablers are analysed in sight of a future application of the FlexPlan methodology for the grid planning activities of the European TSOs and DSOs.

The FlexPlan Consortium encompasses three TSOs (TERNA Italy, ELES Slovenia and REN Portugal); the ENEL Global Infrastructure (also representing the Italian distributor e-distribuzione, present in the consortium as a linked third party); research and development companies and universities from eight European countries (Belgium, Germany, Italy, Norway, Portugal, Serbia, Slovenia, Spain), including the project coordinator RSE; and N-SIDE, the developer of the European market coupling platform EUPHEMIA.
The following chapters summarize the different achievements of the FlexPlan project:

- **chapter 1** provides an introduction to the project motivations and Consortium;
- **chapter 2** provides details on the FlexPlan grid planning methodology;
- **chapter 3** shows the features of the FlexPlan pre-processor;
- **chapter 4** details the features of the grid-expansion planning tool;
- **chapter 5** explains the pan-European model;
- **chapter 6** illustrates features and results of the 6 regional cases;
- **chapter 7** brings the regulatory analysis.

# 1 INTRODUCTION TO PROJECT MOTIVATIONS AND CONSORTIUM

Massive RES deployment will make future transmission and distribution (T&D) grid planning more complex and affected by uncertainty. Grid investments are capital intensive, and the lifetime of transmission infrastructure spans several decades: due to rapidly changing scenario hypotheses, when a new line is commissioned, the foreseen benefits could no longer justify the corresponding investment. Moreover, variable flows from RES are generating a new type of intermittent congestion which can sometimes be well compensated with system flexibility, while investments in a new line would not be justified. For these reasons, it would be worthwhile to investigate alternative ways for compensating peak flows and overcome congestion in the grid by exploiting existing or new system flexibility instead of scheduling an expensive and time-consuming system infrastructure expansion.
On this pathway, storage can provide a good alternative to building new lines. In fact, the placement of storage devices in strategic grid locations could prove effective in preventing temporary line overloading, thus constituting a good alternative to building new lines aimed at coping with RES generation peaks. A similar role could be also taken by flexible consumption (e.g., deferrable consumption), especially when considering big industrial loads and tertiary infrastructures. Finally, as storage capacity and flexible load management should be mostly provided by means of private engagement, special regulatory mechanisms should be devised and enforced in order to incentivise building up new flexibility items in opportune locations, wherever consistent advantages are identified.

Flexibility should not be seen as always preferable to building new lines and cables, but the assessment must be led by taking into account the whole structure of the present transmission and distribution grids as well as the scenarios which are adopted to describe the future evolution of the system, from the mid-term (2030) till the long term (2050), which make the whole investigation extremely complex and challenging from the mathematical point of view. Additionally, traditional tools used by transmission system operators (TSOs) and distribution system operators (DSOs) in order to evaluate grid investment needs are not adequate for this kind of analysis. Therefore, a complete methodological re-thinking is necessary.

All these aspects have motivated the activity of the FlexPlan Horizon2020 project (https://flexplan-project.eu/, active from October 2019 till March 2023), which established an innovative grid-planning methodology considering the opportunity to introduce new storage and load flexibility resources in electricity T&D grids as an alternative to building new grid elements. FlexPlan created a new innovative grid-planning tool whose ambition was to go beyond the state of the art of planning methodologies by including the following innovative features: integrated transmission distribution planning, environmental analysis, probabilistic contingency methodologies (in replacement of the N-1 criterion) as well as optimal planning decision over several decades. The new tool was used to analyse six regional cases covering nearly the whole European continent (Iberian Peninsula; France and Benelux; Germany, Switzerland and Austria; Italy; Balkan Countries; and Nordic Countries). These regional cases are aimed at demonstrating the application of the tool in real scenarios as well as at casting a view on grid planning in Europe till 2050.

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This constitutes the final report of the project, in which a short summary of all activities is provided.

The following chapters will outline:

- the innovative T&D grid planning methodology elaborated by FlexPlan (chapter 2);
- the basic principles used by the FlexPlan pre-processor to propose and prioritize candidates for system upgrade including both flexibility candidates, lines and reinforcement of existing ones (chapter 3);
- the basic principles of the software implementing the FlexPlan grid expansion planning tool (chapter 4);
- the modelling assumptions of the pan-European model run to establish border conditions for the 6 regional cases (chapter 5);
- the sources for input data, the assumption and the main results produced by the 6 regional cases (chapter 6);
- the final regulatory reflections carried out by FlexPlan on the basis of the experience gathered during its activity and the results of the regional cases.

The very final product of the FlexPlan project is a set of planning guidelines and a set of regulatory guidelines, both listed in the chapter "key findings" at the beginning of the present report.

# 2

# A HOLISTIC APPROACH TO FLEXIBILITY-AWARE TRANSMISSION AND DISTRIBUTION GRID PLANNING

## 2.1 THE NEED FOR A HOLISTIC GRID PLANNING APPROACH

For a successful renewable energy transition, massive network reinforcements are needed at all grid levels to accommodate bulk renewable generation sources on the one hand, and small distributed generation on the other. Additionally, a successful renewable energy transition requires the electrification of other used primary energy sources, mainly for the industry and transport sectors. As such, the increase in the electrical energy demand is expected to put even more stress on transmission and distribution grids, which are being operated ever closer to their limits. According to EURELECTRIC[1], distribution grids investments between 375 to 425 billion Euro are needed until 2030. Similarly, ENTSO-E states[2] that annual transmission grid investments of 43 billion Euro until 2040 are needed for renewable energy integration.
To make the energy transition affordable, a holistic grid planning approach is needed, which can assess the trade-offs between classical network investments and flexibility sources across all voltage levels and find the optimal grid expansion strategy for the coming years and decades. The planning approach developed within FlexPlan considers such trade-offs from a social welfare maximisation point of view, accounting for grid and flexibility investments, system operational costs, and the environmental impact of grid extension across transmission and distribution systems.

## 2.2 THE FLEXPLAN MODEL

*Figure 2.1* shows the structure of the FlexPlan optimisation model. A set of candidate grid investments, e.g., alternating current (AC) and direct current (DC) transmission assets, AC distribution assets, demand flexibility and storage investments are provided as an input for the planning model. These expansion candidates are characterised both technically and economically by the FlexPlan pre-processor, explained in detail in the following chapter. The installed conventional power generation capacity, RES generation and demand time series as well as transmission and distribution system data are used as input. The formulated optimisation problem is a stochastic optimisation problem with the aim of minimising the costs for grid investments, system operational costs and environmental impact for a variety of operating conditions and planning years, where the stochastic formulation allows to select the most suitable investments based on the likelihood of occurring operational conditions.

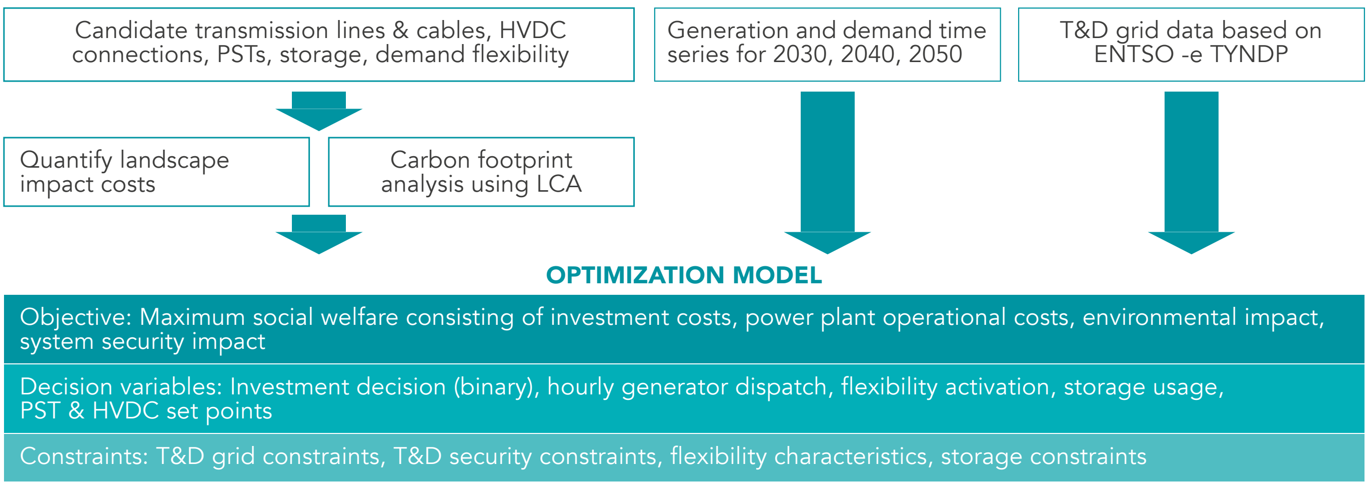



*Figure 2.1: The FlexPlan planning model*

[1] https://www.eurelectric.org/news/pr-connectingthedots/
[2] https://tyndp.entsoe.eu/news/2020/07/upcoming-first-zonal-study-of-pan-european-power-system-needs-by-2040/

As a first step of the planning model, grid expansion, flexibility and storage candidates are assessed based on their $CO^2$ footprint landscape impact (*Figure 2.2* - middle). For all types of candidates used in the planning tool, a life-cycle analysis is performed to determine their carbon footprint which is monetised in the objective function of the planning model.

The landscape impact costs are determined using an optimal transmission routing model, which considers the cost of installation and visual impact for overhead and cable transmission systems for a variety of geographical areas, such as rural and urban areas, mountain regions and protected natural areas both onshore and offshore (*Figure 2.2* - right).

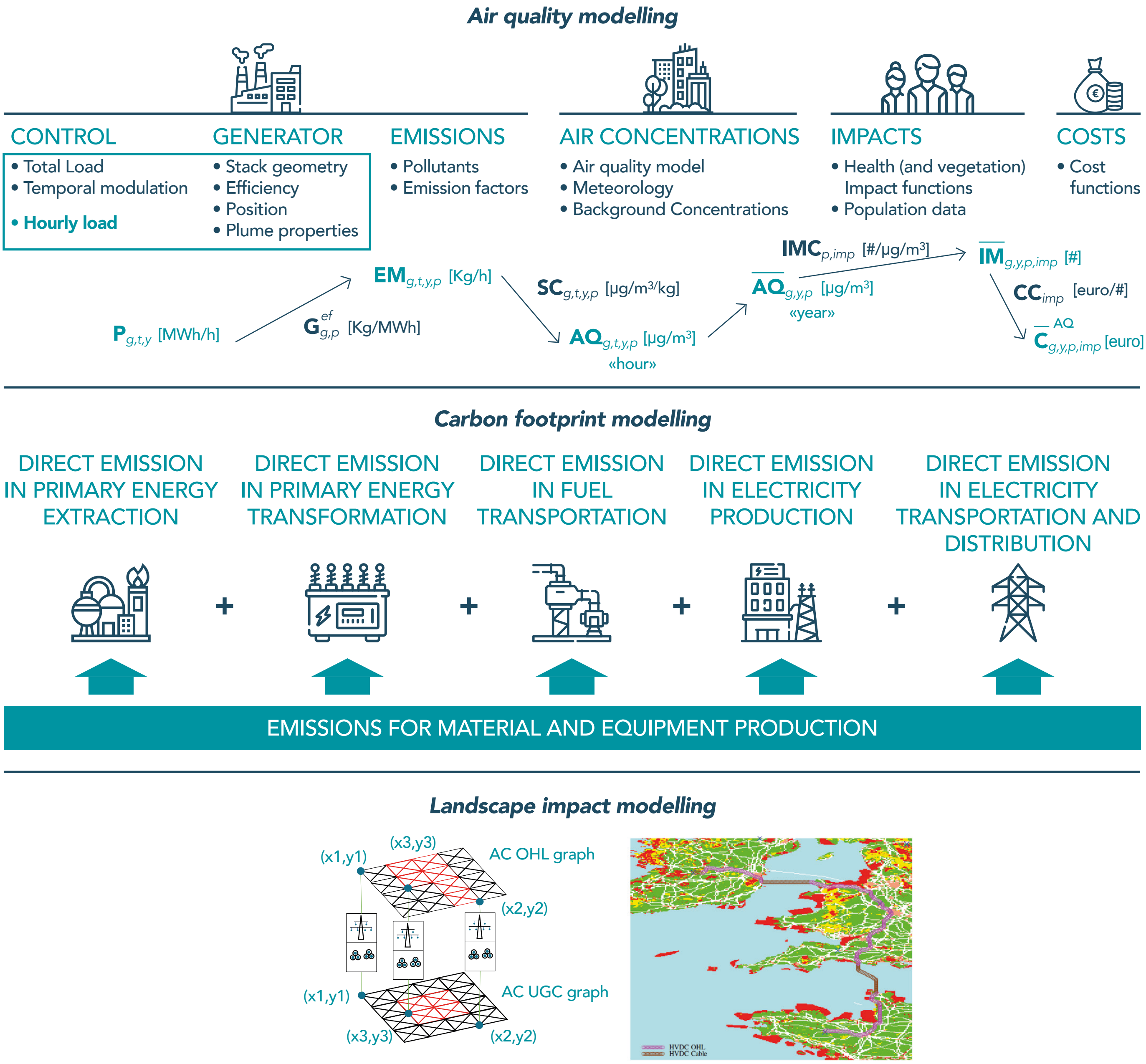



*Figure 2.2: Environmental impact modelling in FlexPlan*

Unlike carbon-footprint- and landscape-related environmental costs, air quality impact-related costs are integrated directly into the objective function of the optimisation.
A linear model air quality impact model is developed, which determines the health impact of emissions from conventional generation based on historical data sets for different geographical regions and climatic conditions. By penalising the conventional power generation costs with the air quality impact costs, the optimisation model implicitly favours the integration of renewable generation sources, and the necessary grid investments to accommodate them (*Figure 2-2* - left).

To make the model applicable to both transmission and distribution networks, the underlying network model is decomposed into two components, namely the meshed and the radially operated networks. This distinction is made independently of the juristic definition of transmission and distribution networks, as these differ significantly among the European countries.

Concerning meshed networks, besides flexible elements, classical AC overhead line and underground cable investments are considered, along with phase-shifting transformers and possible new primary substations. The power flows of both the AC and DC grids are modelled separately in detail. HVDC converter stations are modelled explicitly connecting AC to DC networks and vice versa. Radially operated networks are modelled in detail to consider both thermal and voltage congestion in the system, resulting in a more advanced formulation of the network model including reactive power management of the network. The details of network modelling have been outlined in **Deliverable 1.2.**

Considering that the aim of FlexPlan is to obtain a sequential development plan for storage, flexibility, and network investments for the European region, networks with thousands of buses and branches, and a variety of operational and climatic conditions over three decades (2030, 2040 and 2050) need to be modelled.
The resulting optimisation problem contains millions of decision variables and constraints, with discrete investment decisions which is highly intractable. As such, different model decomposition techniques have been used to keep the tractability of the planning model along with the application of clustering methods for reducing the number of operational conditions considered in the model without compromising on the accuracy of the results.

One decomposition approach used is based on the decoupling of the meshed (transmission) and the radially operated (distribution) networks. The planning problems related to the two network levels are solved sequentially in a three-step procedure. In the first step, each distribution network is considered separately. The optimal set of investments that solves local congestion is determined, then the residual flexibility that the distribution network is able to provide to the transmission network is assessed. This distribution planning approach consists of assigning to the distribution system operator the priority in procuring flexibility sources for local services. However, thanks to the application of opportune weighing factors to the costs associated to line/transformer investments and the ones associated to flexibility exploitation, the distribution network planning can be driven to situations in which the operation priority of local storage and other demand side units is assigned to the transmission system operator.

Once the optimal distribution planning is defined according to the agreed TSO DSO priority, the results are expressed in terms of delivering and absorbing active power to/from the meshed network and encoded in a surrogate model that replicates the behaviour of the distribution network without individually modelling its components. In the second step, the surrogate models of the distribution networks are attached to the transmission network and the optimal expansion plan of the transmission network is computed. In the last step, once the power exchanges between the transmission network and distribution networks have been established, the optimal planning of the distribution networks is finally determined (**Deliverable 1.2**).

To increase the algorithmic performance of the model, different variations of Benders decomposition have been implemented and tested. The main philosophy of the Benders decomposition is to solve the investment problem and the operational problem in an iterative way, such that the discrete optimisation problem becomes leaner. The solution of the investment (discrete) problem builds the lower bound to the optimisation problem, whereas the sum of the investment and operational problems provides an upper bound. In each iteration, the lower and upper bounds are updated using the Lagrange multipliers of the operational problem until convergence between the two bounds is achieved (**Deliverable 1.2**).

## 2.3 INPUT SCENARIO GENERATION AND REDUCTION

In order to provide a set of representative planning scenarios and time series to the planning model, a scenario generation methodology is developed. The developed methodology is used to first generate a large variety nodal generation and demand scenarios in terms of hourly time series, which are reduced to a set of representative time series to decrease the size optimisation problem.

For the scenario generation, the intermittent generation from variable renewable energy sources, the generation of hydro power plants and the electricity demand are considered as stochastic inputs with respect to the grid expansion planning problem.
The developed methodology and implemented prototype consist of the following building blocks:

- a geographic reference system based on approximately 290 locations in Europe for time series data;
- a database, containing meteorological and hydrological information for 40 years;
- a time series generator for wind, solar and hydropower generation sampling;
- a time series generator for demand sampling;
- a method to model temporal and spatial correlations of the aforementioned time series;
- a methodology to reduce the huge amount of operational scenarios formed by the aforementioned generation and load time series to a representative set.

For the scenario generation, the temporal and spatial correlations between the stochastic inputs have been considered. Using the developed methodology, hourly time series for all afore mentioned stochastic inputs have been created for 35 different climate years (**Deliverable 1.1**).

After analysis of different scenario reduction techniques and after assessing their performance in capturing the uncertainty space with a limited number of scenarios, finally, a K-means clustering approach is used to reduce the number of operational scenarios to keep the optimisation problem tractable. Starting from the full uncertainty set of climatic conditions (35 years in hourly resolution), time series for the stochastic inputs have been reduced to a reduced set of climatic variations on the one hand, and to a number of representative weeks within these climate years on the other, achieving a significant reduction of the size of the optimisation problem (**Deliverable 1.1**).

## 2.4 OPEN-SOURCE IMPLEMENTATION AS PROOF OF CONCEPT

Two open-source software packages have been made available to the public as part of the proof-of-concept testing of the developed methodologies.

The first software package is *FlexPlan.jl* which serves as a design reference for the FlexPlan planning tool implemented in Julia/JuMP. Using the *FlexPlan.jl* package, small scale test cases can be solved using a variety of commercial and open-source optimisation solvers (*Figure 2.3*).

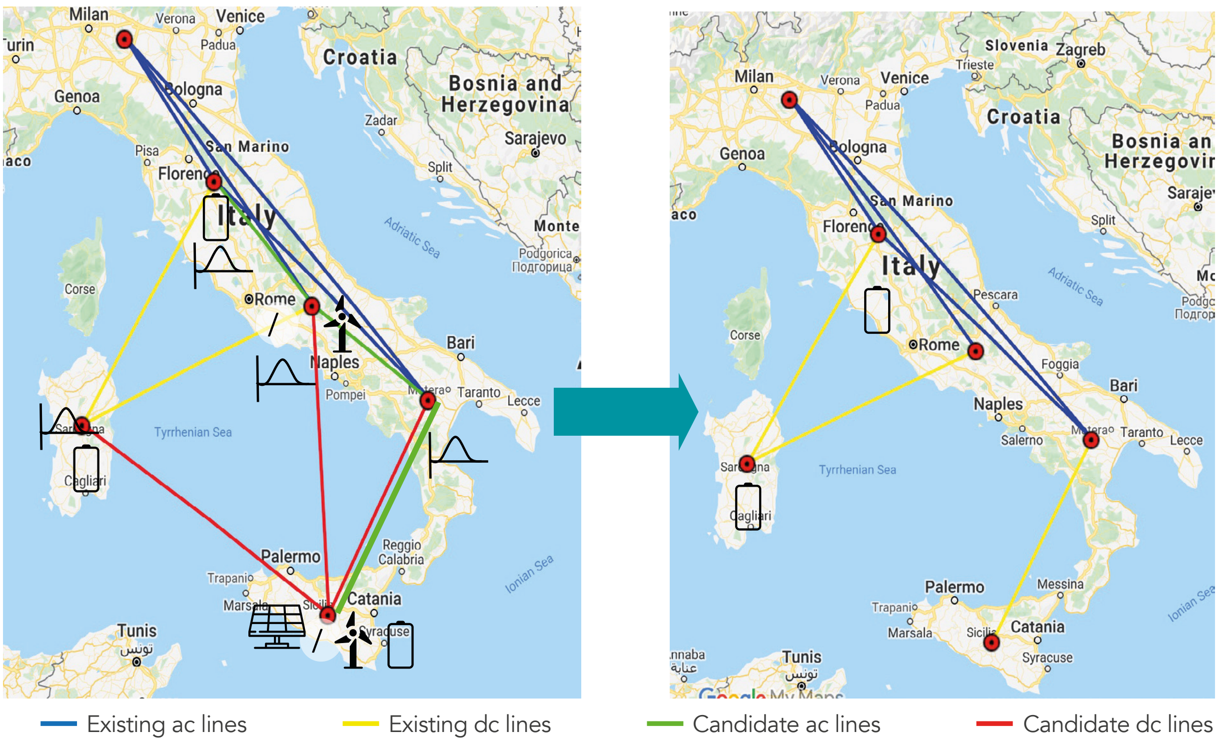



*Figure 2.3: Solving the planning problem using FlexPlan.jl*

This implementation also allows to quickly implement and ,test new features for the planning model in an agile way. FlexPlan.jl considers AC and DC transmission networks, includes storage and demand flexibility models both for existing infrastructure and for a set of defined candidates. For distribution systems only AC networks are considered. FlexPlan.jl allows time series input for renewable generation and demand, for number of grid planning years, and scenarios defined by the user. Some modelling features are:

- multi-period, multi-stage formulation to model a number of planning years, and planning hours within years for a sequential grid expansion plan;
- stochastic formulation of the planning problem, based on scenario probabilities for a number of different time series;
- linearized power flow model of AC/DC transmission grids, and the linearised DistFlow model considering reactive power and voltage magnitudes for radial distribution grids,
- extensive, parametrized models for storage, demand flexibility and DC grids;
- different Benders decomposition methods for solving the large-scale MILP problem;
- decomposed solution of the transmission and distribution system planning models.

Installation instructions, information regarding problem types and network formulations are provided in the package documentation (https://electa-git.github.io/FlexPlan.jl/dev/). The installation contains several different test scripts and test system data for various academic test cases, both for transmission and distributions systems.
The source code can be found under: https://github.com/Electa-Git/FlexPlan.jl.
The current release version is v0.2.2, and the package is continuously extended with more example scripts, test cases, additional problem types and improvements on documentation.

The *OptimalTransmissionRouting.jl* package is a Julia/JuMP package to determine the optimal transmission system route considering spatial information which allows to assess the landscape impact costs of new investments. *OptimalTransmissionRouting.jl* serves as part of the pre-processor routine of the FlexPlan approach which is outlined in the following chapter. The implemented method uses spatial information coming from an image file and converts them into a weighted graph. To that end, spatial information from http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2 is used. The created array represents a weighted graph connecting several nodes horizontally, vertically, and diagonally with graph weights reflecting the area dependent investment and installation costs of the investments for each region of the map. Finally, using a modified A-star algorithm, the shortest path in this weighted graph is found, which provides the least cost transmission path. The developed implementation supports underground and overhead transmission (including partial undergrounding) for both AC and DC grid expansion (***Figure 2.4***).

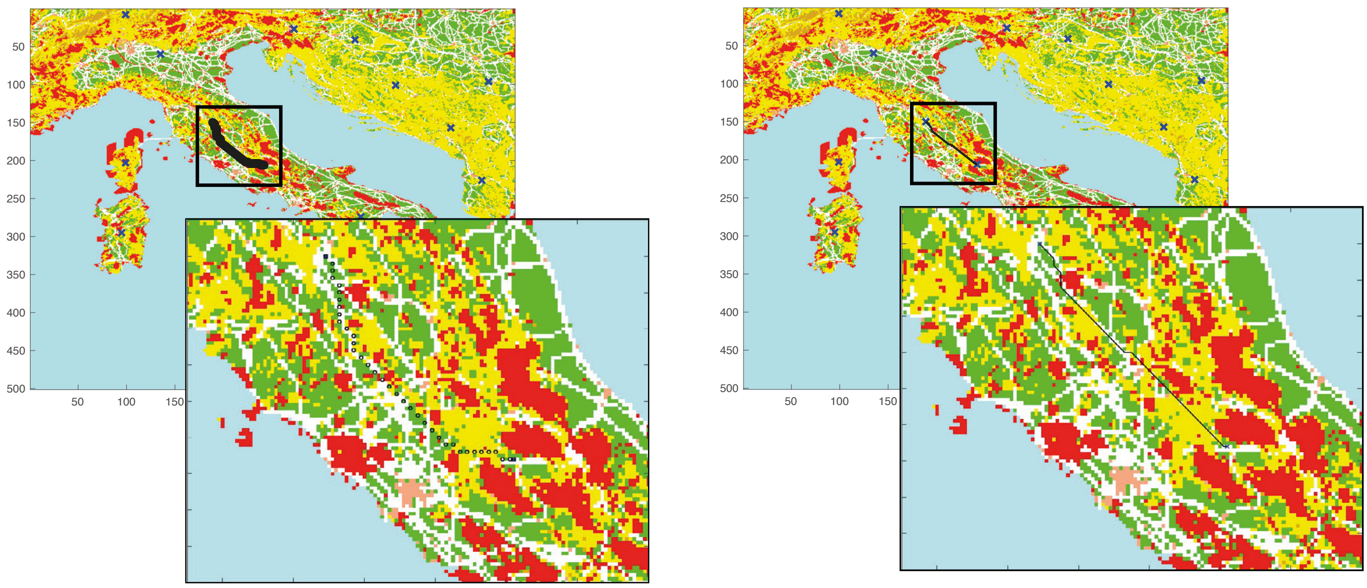


*Figure 2.4: Optimal transmission routes for overhead lines (left) and underground cables (right)*

The *OptimalTransmissionRouting.jl* package has been published as an open access license toolbox and can be found on:
https://github.com/Electa-Git/OptimalTransmissionRouting.jl and its documentation can be accessed through https://electa-git.github.io/OptimalTransmissionRouting.jl/stable/ or by clicking at the documentation button on the GitHub repository. The current version is v0.1.4.

# 3

# STORAGE AND DEMAND RESPONSE TO REINFORCE THE ELECTRICITY NETWORK

## 3.1 FLEXIBILITY CANDIDATES IN THE PLANNING PROCESS

In the past, conventional electricity grid extension planning has been focussed on the installation of new network assets, such as lines, substations, etc., to cope with demand increase. However, in the last years new paradigms of power generation and demand have arisen. On the one hand, distributed generation is continuously growing in the lowest voltage levels, at distribution network. On the other, because of this, demand has become more flexible and, in many cases, a power generation entity, either individually or grouped under energy communities, for example.

The EC in its strategic long-term vision for a climate neutral economy, COM(2018) 773, seeks to have, at least, an 80% share from renewable energy in 2050. Integrating such an amount of variable and hard to predict energy into the power system remains a challenge. In the same communication, the EC explicitly refers to fast reacting generation, storage, and Demand Response (DR) as flexibility sources to integrate renewables into the system. However, some of these technologies, such as storage (other than pumped hydro) and demand response, have not been considered in grid planning procedures up to now.

Storage can behave both as a fast-reacting generation and as a load and, therefore, it is an optimum candidate as flexibility provider. Energy storage is a concept that can be materialized through several technologies. Both transmission and distribution network operators require services from third parties to manage the energy system within safe limits and the expected quality level. Storage can provide most of the requested services at system and network level (**Deliverable D2.1**).

Another promising flexibility provider is demand. It is expected that demand will participate more and more in energy markets. Demand Response strategies can reshape demand profiles to cope with renewable generation variability. Apart from big industrial and commercial consumers, smaller customers will be able to offer their flexibility through aggregation (**Deliverable D2.1**).

The network planning methodology developed in FlexPlan, considers both storage and demand response as candidates for network expansion, both in the transmission and distribution networks. The planning tool tries to optimize a cost function, which considers in addition to fuel costs also environmental impacts. The tool provides as output the network investments that make network planning effective in terms of generation meeting demand, and less expensive, by choosing among conventional assets, storage and demand the most appropriate solutions.

This methodology has more challenges than considering new flexible elements and both transmission and distribution in the planning: candidates are considered for several network locations and for different time frames. This means that several candidates are proposed for different locations in the network and for three decades investment periods (2030, 2040, 2050), and that the planning tool choses which of them should become expansion investments and when this investment should be done to achieve the lowest cost for the system. On the top of this, three demand and renewable generation scenarios are considered, each of them with meteorological variants, to take into consideration the renewable resource availability and the demand variation throughout the past years.

The above-mentioned approach considered by the FlexPlan methodology requires a high computational effort to solve the system cost optimization problem and provide a grid expansion planning solution. Many different techniques are implemented to make the problem numerically tractable and, in addition, a software (SW) module has been created and integrated with the planning tool to perform a pre-selection of network investment candidates to support the planning problem: the candidate pre-processor.

Instead of considering every node (location) of the network and every technology as candidate, this software performs a pre-selection of locations and technologies, to restrict the number of related binary variables in the problem. In addition, a price and a cost are provided for each technology, which reduces again the number of possible investment options (Deliverable D2.3).

- The candidate pre-processor software gives response to the following requirements:
- It must be integrated with the planning tool in an automated way: results are exchanged between both applications to permit an iterative process, which starts with the introduction of the network model and scenarios) by the user and ends with the optimal grid expansion solution for the studied period provided by the planning tool.
- The congestions in the system must be identified using the results of an Optimal Power Flow (OPF), which means that the power flows in branches are limited to their nominal capacity (congestions cannot be identified looking at the electrical current values).
- Storage, Demand Response (DR) and conventional assets should be proposed as candidate for network expansion. They could be located at any node in the system, but a pre-selection of locations and technologies needs to be done to reduce the dimensionality of the problem.
- An estimation of size and price needs to be provided for every selected candidate, as input for the planning tool. Providing only one size and price per candidate prevents the number of candidates from growing.

## 3.2 POWER FLOW CONGESTION IDENTIFICATION

The main input source to perform the selection of congested scenarios is the planning software suite, which performs an OPF on the input grid and scenarios before calculating any optimum expansion (non-expanded OPF).

The OPF provides a constrained solution and, therefore, power flows through branches result below or at the capacity limits of each network asset, i.e., are not an indication of congestion. By contrast, four types of outputs are provided by the OPF solver and are used by the pre-processor:

- Lagrange Multipliers (LM) of branches permit to identify congested lines. A LM matrix is created, which includes the LMs for the whole period under analysis in hourly intervals. LMs represent the system cost reduction obtained when sending an additional MW through a branch. If the value is different from zero, this means that the line is congested. ***Figure 3.1*** shows an example of the branches and transformers (in red) with LMs different to zero in the Iberian Regional Case (Portugal and Spain).

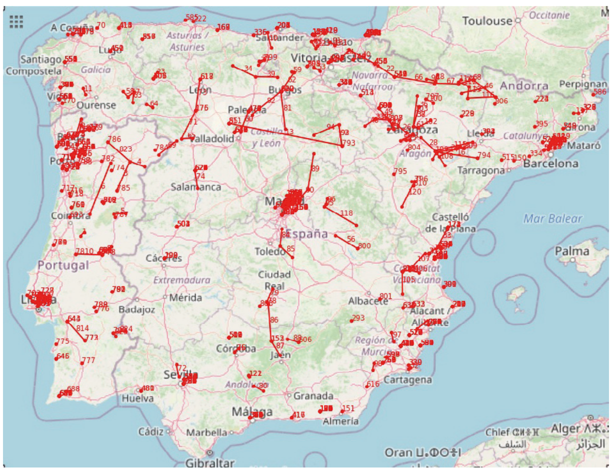



*Figure 3.1: Branches and transformers with LMs different to zero in the Iberian Regional Case*

- Locational Marginal Prices (LMP) provide useful information for the location of flexible resources (storage and DR). They represent the cost increase in the system when an additional MW is requested by demand at a bus. If no congestion exists in the system, all nodes have the same LMP values. A higher LMP at a bus means that an increase of demand at that bus will increase system costs more than the demand increase at a bus with lower LMP.
- The Power Transfer Distribution Factors (PTDF) permit to analyse the change in the active power flow through network branches, as a consequence of increasing their capacity. A PTDF matrix is created, with system branches in rows and buses in columns. Matrix values indicate the portion of power injection in a given node that flows through a given grid branch.
- Power flows through the branches and transformers in the system provide the saturation level of branches.

In a first step, the pre-processor checks the LM matrix for the grid model under study. A matrix is created for each year, representing one decade, with hourly LM values. The grid model input data includes demand and renewable energy data from various meteorological variants and their related probability (extracted from 35-year data). The LMs resulting from the OPF are representative of this input information.

By checking the LMs, congestion occurrence and severity are studied, and a ranking is created for all the branches and transformers of the system. The probability assigned to each scenario variant is also used to provide a weight to the congestions identified in each of them.

Based on the ranking, the most congested branches and transformers both in transmission and distribution grids are selected. These assets reflect the most congested areas in the system and, therefore, a possible location for network extension, either for a storage, for a flexible load (DR) or a conventional network asset (new line, cable or transformer).

For each of the selected congested lines, the characteristics of the congestion are analysed in a more detailed way: power flow direction, total number of congestion hours in a year and the number of consecutive congestion hours. The characterization of congestions is used discard those technologies not suitable to solve them, which involves reducing the dimensionality of the optimization problem. *Figure 3.2* summarizes this phase.

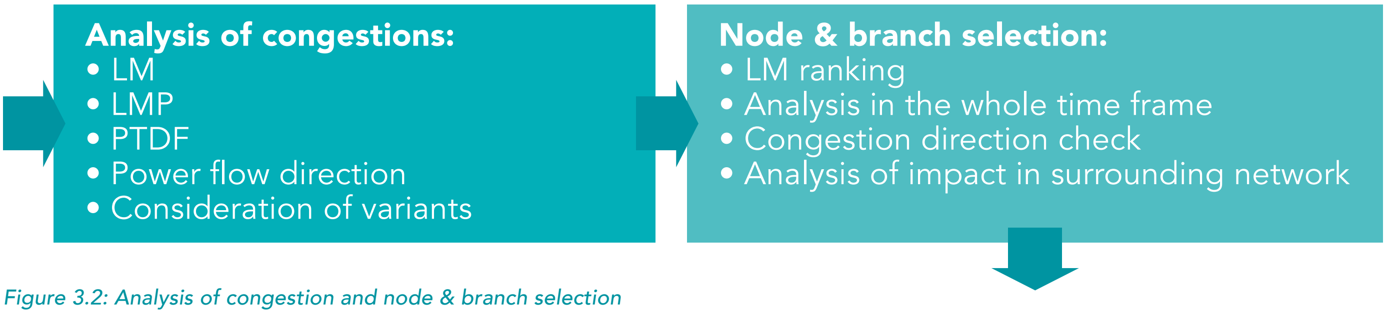



*Figure 3.2: Analysis of congestion and node & branch selection*

## 3.3 SELECTION OF FLEXIBILITY CANDIDATES

The candidate pre-processor aims at proposing a set of network expansion flexibility candidates targeting at the resolution of the existing congestion at each of the selected branches in the previous step.

The flexibility technologies considered by the pre-processor as candidates are the following (**Deliverable D2.2**):

- Storage: batteries (lithium-ion, NaS and flow), pumped-hydro, hydrogen, compressed air storage (CAES) and liquid air storage (LAES),
- Demand Response (DR): through flexible loads,
- Conventional network assets: lines/cables (AC, HVDC) and transformers,
- Phase-Shifting Transformers (PSTs).

Two ways are possible to propose candidates to the planning tool: forced by the user and automatically calculated by the candidate pre-processor module.

The user can propose candidates for those technologies that require a specific study, which would be very hard to assess automatically in a proper way: HVDC connections, PST systems and pumped-hydro power plants.

On the contrary, for the other technologies, the candidate pre-processor proposes network investment options automatically. For all locations where a congestion is identified, the suitability of each technology is checked through the analysis of local constraints and the characteristics of the congestion. Congestions are characterized through the analysis of the non-expanded OPF results, as described before. In the case of the locational constraints, as part of the grid model definition, users can provide additional characteristics related to each network node. The selection of candidates at a specific location is screened according to this characterization: as the congestion characteristics, the network information provided for nodes are used to discard, or not, some of the candidate technologies.

In the planning tool developed in FlexPlan, the user can assign the following characteristics to each of the nodes (buses) of the grid model:

- Type of bus: substation, load, power plant,
- Availability of natural resources: cavern (to check the suitability to install CAES), water,
- Location of bus: urban, semi-rural, rural,
- Geographic characteristics (for rural buses): mountainous, plain,
- Restricted area (not allowed to build new installations): total or for certain technologies.

It is not mandatory to provide all this information, but it helps refining the candidate pre-selection, so it is recommended to include it, at least, for those the nodes affected by congestions. If one or more technologies are not suitable for a location, they are not included in the candidate list that the pre-processor provides to the planning tool.

In order to perform this assessment automatically, a heuristic approach is assumed to check the constraints and characteristics of the model and scenario variants.

Once the most suitable technologies have been selected for a location, the pre-processor provides a size and cost for each of them. The estimation of the size and price of the candidates is based on literature and on the existing network characteristics, but it can be configured in the pre-processor.

In the case of lines, an additional check is carried out. Solving the congestion in one branch of the network, e.g., adding new capacity between two nodes, may cause new congestion in other surrounding branches, because of the new power flow. This is especially relevant for meshed networks. In order to avoid that an investment turns out ineffective, because congestion is just moved from one branch to another, PTDFs are used to estimate how the increase of capacity in one line may influence the saturation in other lines. *Figure 3.3* depicts the example of a congested line in the Spanish 132kV network (from Sagunto to la Eliana) and the surrounding lines with higher PTDF values in a grey scale (white: low influence; black: high influence).

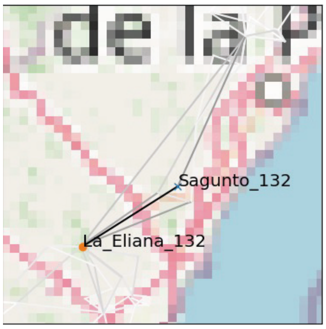



*Figure 3.3: Example of a congested line in the Spanish 132kV network*

*Figure 3.4* summarizes the final steps performed by the candidate pre-processor.

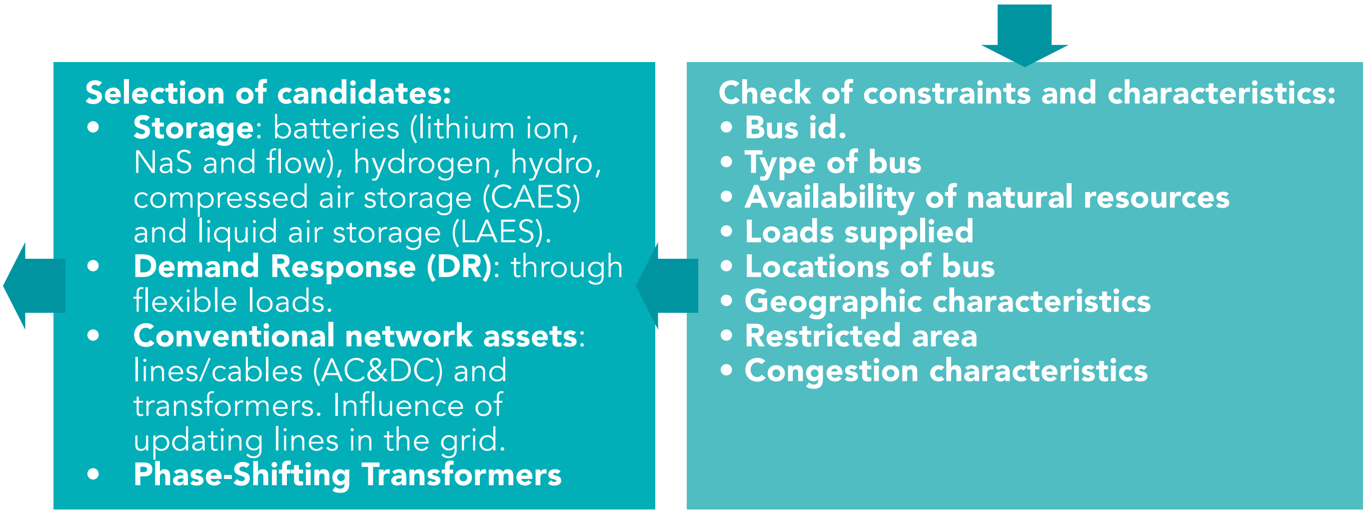



*Figure 3.4: Final phases of the pre-processor*

# 4

# ROBUST, SECURE AND LARGE-SCALE IMPLEMENTATION OF THE PLANNING SOFTWARE

In order to test the new holistic grid expansion planning methodology defined and described in chapters 2 and 3, it was required to implement the newly defined process in a robust, scalable and secure software.

To make it easy to use and access, the planning engine was hosted in the AWS cloud[3], with one deployment per end-user accessible through an Application Programming Interface (API) and Graphical User Interface (GUI).

The innovative planning engine was developed with state-of-the-art technologies such as Python[4] as programming language, IBM CPLEX[5] as mathematical optimization solver, DOcplex[6] as programming interface with IBM CPLEX, and custom JSON[7] as Input/Output data format. As a future extension of work, accepting CGMES files[8] as Input/Output format will allow to reduce the time needed for a new end-user to prepare the data to start using the software.

## 4.1 THE FLEXPLAN FULL PROCESS

*Figure 4.1* depicts the flow of the full FlexPlan methodology implemented in the planning engine. This flow can be described as follows:

1. First, the end-user provides the input data, consisting of Generic Parameters, transmission and distribution Grid Model and Future Scenarios (load and renewable generation profiles) to the FlexPlan Planning Tool. This can be done either through the API or through the GUI.
2. Then, the FlexPlan Planning Tool executes a non-expanded Optimal Power Flow (OPF) in order to identify the existing bottlenecks in the grid, such as congested lines and buses with high Locational Marginal Prices.
3. Those results are then being sent to the FlexPlan Pre-Processor (described in chapter 3) to be analysed in order to generate potential reinforcement candidates. Those candidates can be new classical assets such as new lines but also demand response programs or storage units as prescribed by the new methodology.
4. Once the candidates are generated, the FlexPlan planning tool solves the Grid Expansion Planning (GEP) problem in order to select the set of candidates that minimizes the total costs (sum of investment and operational costs).
5. Finally, the results are retrieved by the end-user through the API or the GUI.

[3] https://aws.amazon.com
[4] https://www.python.org
[5] https://www.ibm.com/products/ilog-cplex-optimization-studio/cplex-optimizer
[6] https://www.ibm.com/docs/en/icos/22.1.1?topic=docplex-python-modeling-api
[7] https://www.json.org/json-en.html
[8] https://www.entsoe.eu/data/cim/cim-for-grid-models-exchange

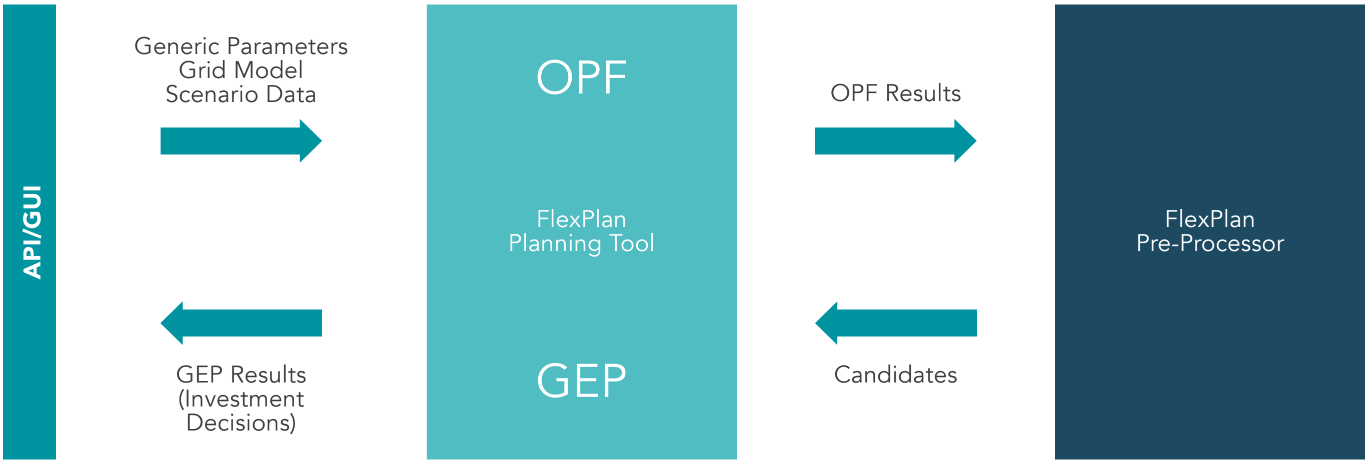



*Figure 4.1 – Flow of the FlexPlan Full Process*

Furthermore, it is important to note that the planning engine is also able to reduce the number of inputted scenarios and/or extract representative weeks from those scenarios. This is being done by applying the k-means clustering algorithm[9] on primary features of the scenario time series, such as the mean and the variability of the load, wind generation and solar generation.

## 4.2 SECURITY MEASURES TO REDUCE VULNERABILITIES

Being the FlexPlan grid planning tool hosted in the AWS cloud, it was fundamental to implement a series of security measures in order to reduce the risk that the tool is accessed by unauthorized people or that the processed data is accessible by malicious people.
Therefore, the planning tool engine features the following security measures:

- IP whitelisting, a security feature used to limit and control the access to the tool to trusted users;
- extension of the HTTP protocol to HTTPS, commonly used for secure communication over a computer network (encryption during transfer);
- basic authentication, ensuring that each end-user has its own username and password, so their simulations can only be accessed by those who have those keys available;
- input handling in a way that the sensitive input data is only kept during processing and not persisted to drives afterwards.

## 4.3 CORRECTNESS OF THE IMPLEMENTATION

To ensure the correctness of the implementation of the new planning methodology, the planning engine was also deeply tested. Firstly, components tests were conducted by comparing the results of the Proof-of-Concept implementation with the results of the large-scale planning software on relatively simple grids, such as the IEEE6 test case. The percentage of number of lines of code (coverage) which is being tested with the procedure reaches 80% for the API, 83% for the OPF and 95% for the GEP and T&D decomposition. Then, end-to-end tests have also been performed to ensure that the full FlexPlan process flow was working, from input files upload to results download, and also testing the integration between the FlexPlan pre-processor and the FlexPlan planning tool. Finally, performance testing was also performed to fine-tune the parameters of the mathematical optimization solver, IBM CPLEX.

## 4.4 IMPLEMENTATION CHALLENGES AND SOLUTIONS

In order to facilitate the implementation work, the FlexPlan planning software was developed in an iterative way, starting from a simple connection prototype until the full software which includes all the needed features. This allowed to be agile in the implementation and to reorganize the roadmap based on the faced challenges.
First, data transfer had to be optimized as the size of data to be uploaded to the server was significant (especially due to future scenarios time series). The custom JSON format was optimized and GZIP compression handling was implemented to reduce the data transfer time.
Then, due to the size and complexity of the test cases, some memory and performance issues were encountered. Some of the first limitations were overcome by increasing the size of the servers (in terms of memory available, and computing power) and implementing the two types of decompositions identified during the development of the methodology:

- Benders decomposition;
- Transmission and Distribution decomposition.

[9] https://en.wikipedia.org/wiki/K-means_clustering

Those decompositions helped to reduce the complexity of the FlexPlan full process. However, it was not sufficient and thus it was also needed to reduce the size and complexity of the Regional Cases. In particular, it was found that units that interconnect multiple time-stamps (such as storage units and pumped hydro) tend to scale exponentially the difficulty of the optimization problems. To overcome this challenge, a limited number of representative weeks were extracted from yearly time series and the granularity of the tool was increased to 2h instead of 1h. Similarly, increasing the number of candidates in the transmission system is one of the main parameters defining the computational complexity of a regional case. This constatation led to the decision to limit the number of candidates per simulation to 100 (which could be easily split between a maximum number of candidates for transmission and a maximum number of candidates per distribution system). All these simplifications were necessary to bring to completion the simulations of the 6 regional cases (see chapter 5), but could be removed in the future wherever the planning tool is deployed in a more powerful HW environment.

Finally, some of the CPLEX parameters were optimized, as explained in the testing section.

## 4.5 GRAPHICAL USER INTERFACE

As an alternative to the API, and in order to ease the use of the FlexPlan planning tool, the user has also the possibility to access it through an intuitive Graphical User Interface. This interface gives him not only the opportunity to use the same features of the FlexPlan planning engine than with the API but also to visualize in an attractive way the inputs and results of the simulations. The user interface was developed with state-of-the-art technologies such as the Django framework[10] for the back-end and Vue.js[11] for the frontend. The library which is used for map visualization is Maplibre[12] . This library was selected because it is interactive, lightweight and customizable.

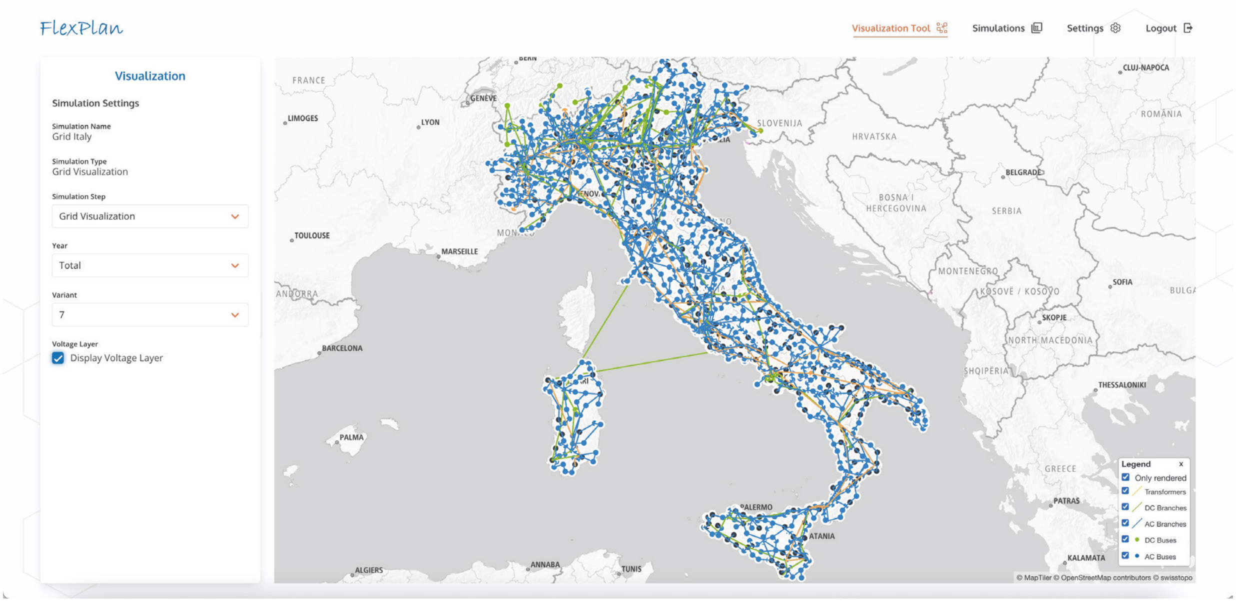



*Figure 4.2 – Grid visualization with voltage layer*

A demo version of the FlexPlan planning tool is available at the following URL: https://flexplan.eu.n-side.com/. This demo version has the goal to give the possibility to external stakeholders such as TSOs, DSOs and regulators to access and test the tool with simple test cases. It allows to run and analyze simulations with up to 20 buses (AC or DC buses). Credentials allowing to test this demo version of the software can be requested by writing an email to flexplan@n-side.com. The same email address can be used to request information to access the full version of the software.

[10] https://www.djangoproject.com
[11] https://vuejs.org
[12] https://maplibre.org

# 5

# A SET OF SCENARIOS FOR A PAN-EUROPEAN ANALYSIS

As the grid planning tool developed in the scope of the FlexPlan project is applied and validated with different regional cases, scenario data is needed and a pan-European simulation is carried out, ensuring the coherence for the following regional studies. The activity described in the present section elaborates a pan-European analysis in order to generate homogeneous input data for the six regional cases covering almost all central and Western Europe as well as the Nordic countries, as indicated in *Figure 5.1*.

*RC1 Iberian Peninsula*
*RC2 France & BeNeLux*
*RC3 Germany, Switzerland & Austria*
*RC4 Italy*
*RC5 Balkan Region*
*RC6 Northern Countries*

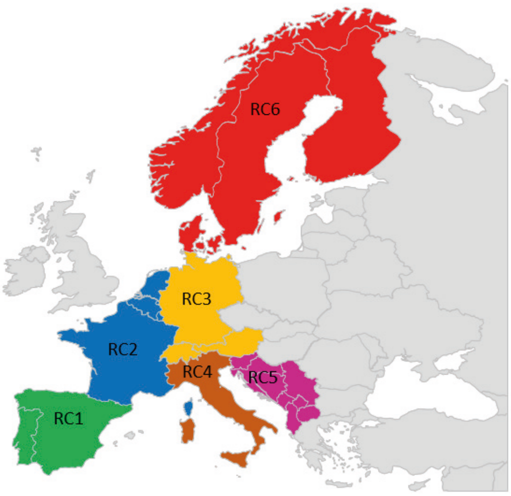



*Figure 5.1 – Scope of FlexPlan Regional Cases*

For this, in a first step, three pan-European scenarios are defined for different target years based on an extensive data collection process, taking into account different restrictions concerning primary energy resources, socio-political, environmental, and economic aspects. The scenarios are used to study potential key factors that result in an increasing variable renewable generation capacity, affecting system planning and operation in a significant way. In a second step, a pan-European simulation is carried out for each scenario at each target year. For this, firstly, national scenario data are broken down to a regional level and renewable energy sources feed-in and load time series are generated by means of a regionalization methodology. Furthermore, secondly, a market simulation is executed, in order to calculate the economic dispatch of the thermal power plants and determine cross border exchanges. The obtained boundary conditions provide a common ground for the regional case studies (described in chapter 6).

## 5.1 PAN-EUROPEAN SCENARIO DATA

The pan-European scenarios are defined at the target years 2030, 2040, and 2050, as it is the time horizon for reducing emissions to net-zero. For each target year three different scenarios are examined in order to model divergent political and regulatory policies, resulting in a set of nine scenario variants. The scenarios need to take into account different restrictions in using primary energy resources such as coal, oil, gas and nuclear fuel.

Economic, socio-political, and environmental aspects are taken into account as well. The main source for the scenarios considered in the FlexPlan project is the TYNDP (Ten-Year Network Development Plan) 2020[13], developed by ENTSO-E, which presents three different scenarios: National Trends, Global Ambition and Distributed Energy. While the National Trends scenario considers the national energy and climate targets of the member states, the other two are completely energy-based and take into account all kind of energy (not only gas and electricity) with the target to reduce emissions to zero by 2050. The Global Ambition scenario implements centralized generation whereas the Distributed Energy scenario considers the integration of consumers into the system. Using this data source, it was possible to create scenarios for 2030 and 2040 with only minor adaptations, due to the absence of some data. However, TYNDP 2020 does not contain data for 2050; hence, a linear interpolation of available data for 2030 and 2040 was implemented in order to create the corresponding 2050 scenarios. Finally, the obtained values were validated and adapted using "A Clean Planet for All" long term strategy from the EU Commission as a comparative source. Since TYNDP 2020 scenarios are built already using this source as a background, the validation process ensures the coherence of the three scenarios at three target years. The final scenario data are shown in *Figure 5.2*.

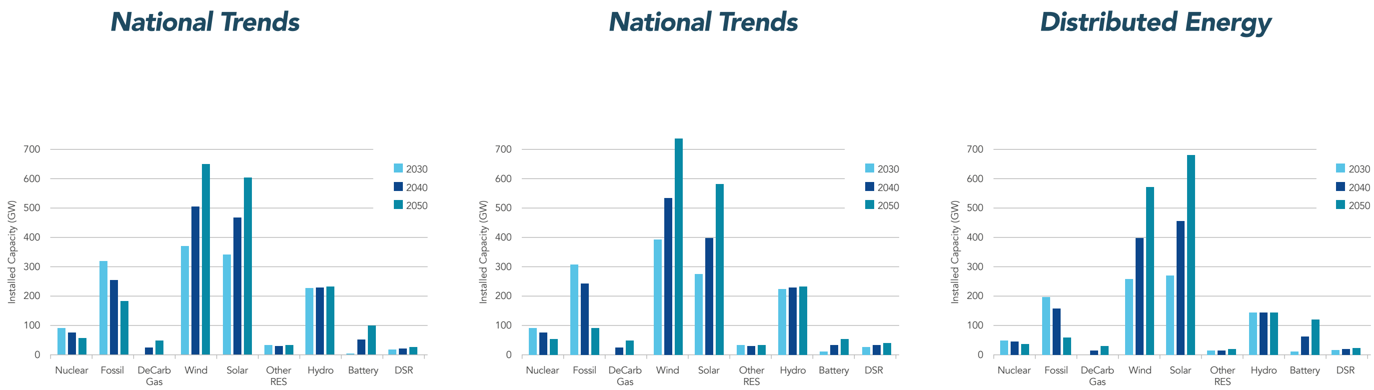



*Figure 5.2 – Scenario data for different variants and years*

In addition to the scenario data, the regional case studies require information on grid models, including topologies and node locations as well as other complementary data, e.g. a power plant data base. The main source for the grid model is the Pan-European transmission grid model from ENTSO-E, which was made available by signing a non-disclosure-agreement. As this data source did not include all the data needed (i.e. the grid model for the Nordic countries was not included), the PyPSA-Eur model[14] was used as a complementary open source model for grid data. More details on the scenario generation and data collection can be found in **Deliverable 4.1**.

## 5.2 PAN-EUROPEAN SIMULATION

As the scenario data is obtained on a national level, it needs to be disaggregated to a regional level, in order to feed the regional cases with nodal information that is coherent with the overall scenario. Furthermore, boundary conditions are needed, providing a common ground for the interrelated regional cases. In order to obtain this information, a pan-European simulation is carried out. The methodology which is applied is based on the market and network simulation environment MILES (Model of International Energy Systems of TU Dortmund)[15].

To generate regional time series for the hourly power injection of renewable energy sources and loads, a regionalization methodology is applied, which is a module of the MILES tool. National scenario data for the different scenarios and target years in used as input data and time series are generated following a two-step approach. First, the national data is distributed to a regional level; as the results are to be used for the regional cases, the regions are defined as the node locations of the transmission grid.

[13] https://eepublicdownloads.azureedge.net/tyndp-documents/TYNDP_2020_Joint_Scenario_Report_ENTSOG_ENTSOE_200629_Final.pdf
[14] https://pypsa-eur.readthedocs.io/en/latest/
[15] https://ie3.etit.tu-dortmund.de/labs-tools/miles/

The installed capacities of generation and load are assigned to these nodes using information on structural data, i.e. population density, as well as information on existing and planned power plants' locations. The structural data is applied to form statistical parameters, which represent proportionalities between land use and installed capacities of RES. For this, regionalization factors are used. Regionalization factors ($F_{Regionalization}$) describe the percentage of the total installed capacity, which is installed in the considered region($F_{Region}$) as shown in the following formula:

$$F_{Regionalization} = \frac{F_{Region}}{\sum_{Region} F_{Region}}$$

Using wind energy as an example, a regionalization factor would be the relation of agricultural area in the region, compared to the whole agricultural area in the country. As a result, more plants are installed in areas with a higher number of agricultural areas.

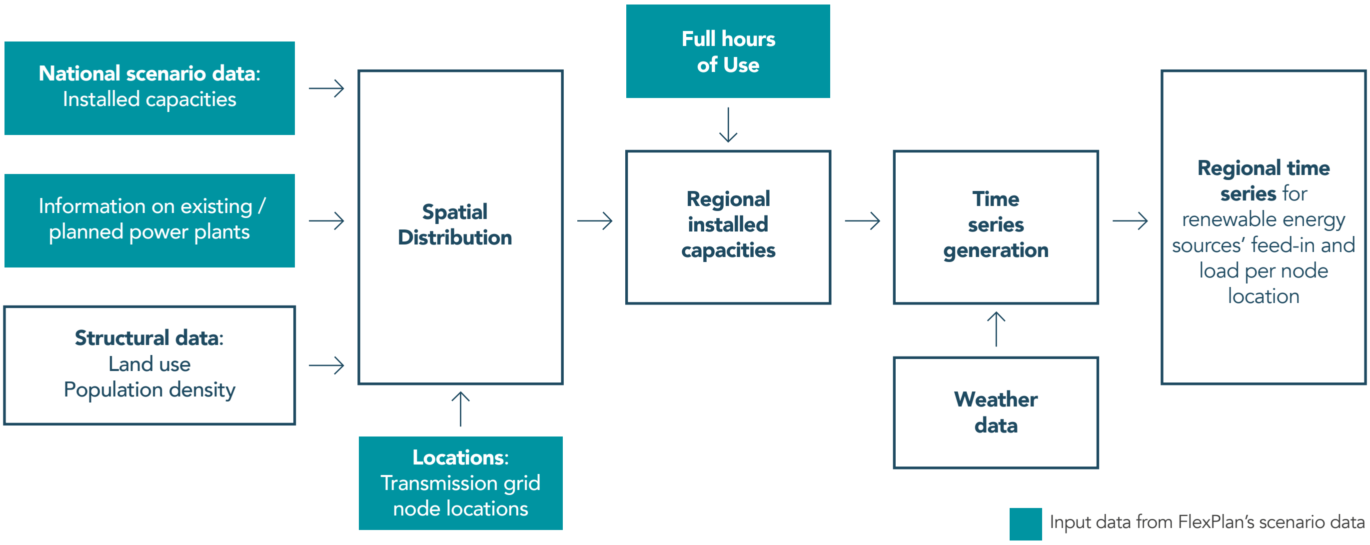



*Figure 5.3 – Conceptual block diagram for regionalization methodology*

In a second step, based on the obtained nodal installed capacities, time series for renewable energy sources are generated using numerical weather models. For this, physical models make use of power functions to transform regional weather data as i.e. wind speed to electrical power generation per node. Load time series are generated by means of disaggregating historical load profiles. Finally, the obtained time series are scaled considering the required energy provided in the scenario data. The methodology is depicted in *Figure 5.3*.

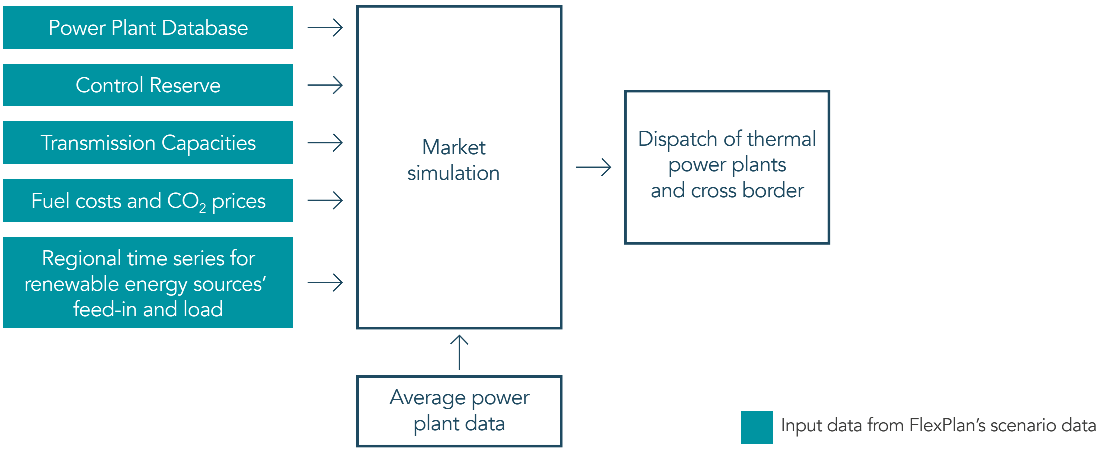
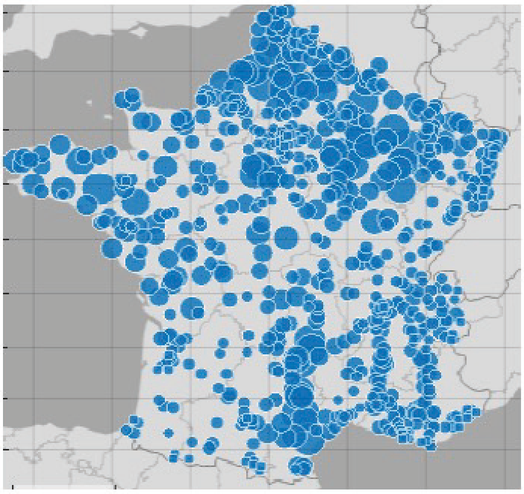



*Figure 5.4 – Conceptual block diagram for market simulation*

Taking into account the calculated time series for renewable energy sources and loads the market simulation module of MILES runs an integrated unit commitment and dispatch model and determines power plant and storage schedules, as well as cross border power exchanges between European countries, as depicted in *Figure 5.4*. The power plant deployment optimization takes into account different constraints i.e., the reserve power to be maintained, available transmission capacities between the countries and the technical, partly time-coupling restrictions of generation units and storage facilities. The resulting power exchanges allow to adopt a consistent set of border conditions for the power flow exchanged between the areas described by the six regional cases.

The regional time series, the power plant and storage schedules as well as the cross-border exchanges, exemplified in *Figure 5* for France, are used as input data for the detailed regional case studies, described in the following chapter. More details on the methodology and the used data for the pan European simulation can be found in **Deliverable 4.2**.



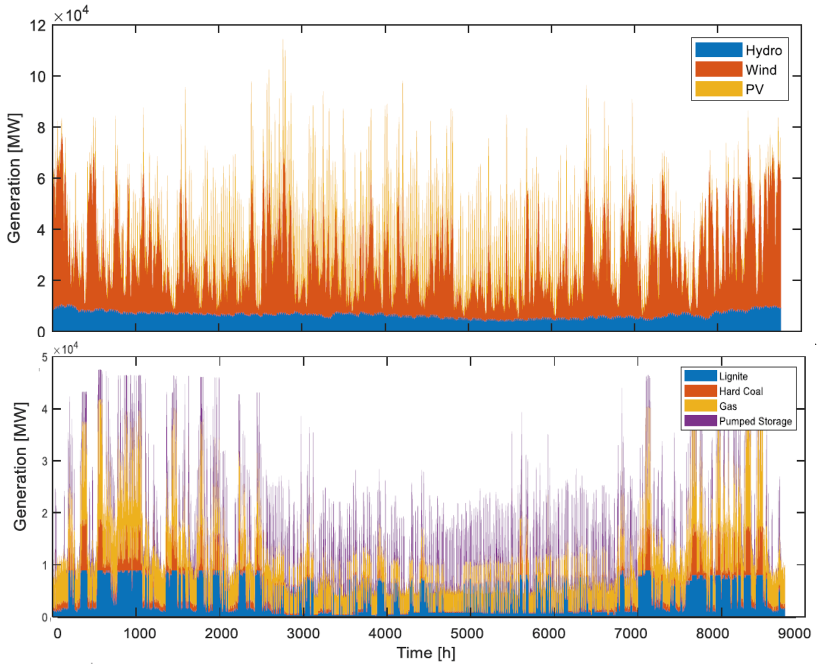



*Figure 5.1 – Distribution of wind power plants (left) and injection of renewables as well as thermal power plants (right) for France*

# 6 REGIONAL CASE STUDIES AND ASSESSMENT OF TESTS RESULTS

The present section provides details on the activities which have been carried out to test the new FlexPlan toolbox on six regional cases encompassing altogether most of Europe (see *Figure 5.1*).

The six regional case studies carried out an analysis of grid expansion planning with time horizons 2030, 2040 and 2050. This process includes:

- gathering preliminary data for the pan-European scenarios, as discussed in detail in Chapter 5;
- evaluating potential candidates for investments in grid expansion, as detailed in Chapter 3;
- carrying out the grid expansion planning studies and analyse the obtained results.

The general positioning of the dix regional studies within the FlexPlan project is shown in *Figure 6 1*.

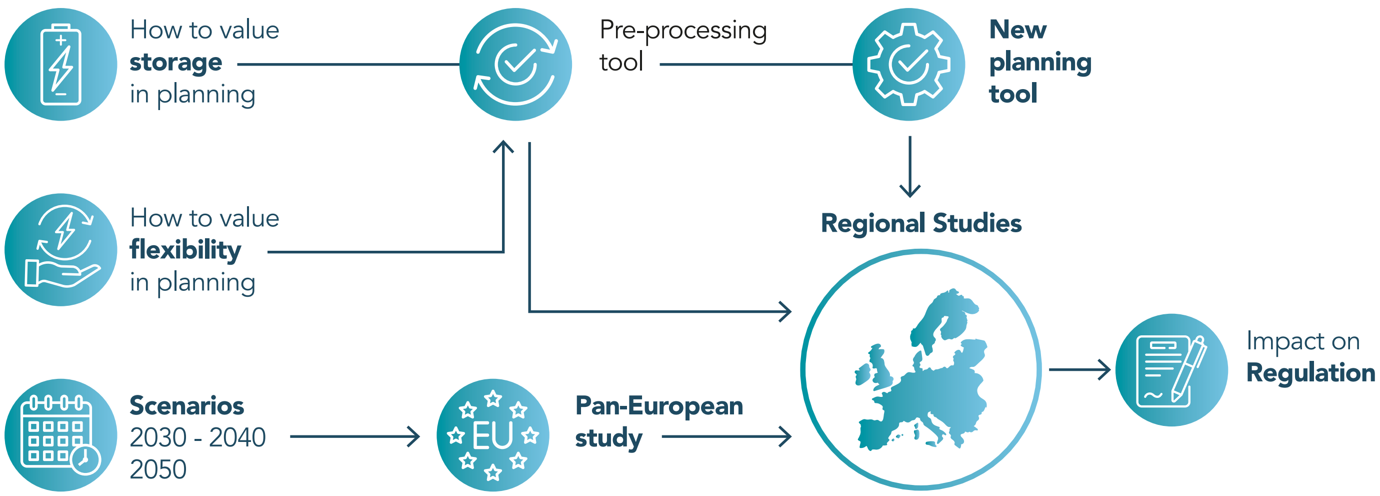



*Figure 6.1 – Overall Project layout*

## 6.1 MODELLING AND PROCEDURES

The data used for network modelling is a critical factor in determining the accuracy of regional case results and investment decisions. It is important to consider both transmission and distribution networks in order to provide grid constraints and define realistic power generation profiles. To get accurate results, it is necessary not only to obtain the data sets required for network modelling, but also to use a common modelling approach for all RCs, determine the principles for localizing load and generation, including the resources located in distribution networks. The regionalized load and generation data obtained from the pan-European market simulations is further localized by fitting them to more detailed regional grids. This is achieved by taking into account the distribution of renewable energy sources and cross-border flows and considering distributed energy sources located in distribution networks. The localization process also involves fitting energy storage systems and flexible loads into the regional grids, taking into account their local impact.

The first step in the creation of the regional cases consists of obtaining data for representing the transmission and sub-transmission networks. To ensure consistency across all cases, a common base dataset is chosen. After an initial investigation, the dataset provided by ENTSO-E for the preparation of TYNDP 2018 scenarios was selected as the base dataset. This dataset contains a pan-European transmission system model for 2025, which serves as the base year for TYNDP studies. However, the grid model received from ENTSO-E did not have all the necessary information required for the scope of the project. Three main data gaps were identified:

- non-existence of sub-transmission systems for major countries, including Spain, France, Germany, and Italy;
- non-existence of grid models for northern countries, such as Sweden, Finland, and Norway, and only a partial model for Denmark (continental part only, in the continental Europe synchronization zone);
- Non-existence of geographic information, and in some cases, anonymization of grid node names.

To overcome these limitations, a complementary and complex data collection process was performed. This activity includes analysing different data sources and aims to solve the three main data gaps identified. The data collection process includes a combination of primary and secondary data sources. The primary data sources include publicly available grid models, grid operator data, and energy market reports. Further data sources include academic journals, technical reports, and other relevant literature.

Since the evolution of the generation mix and demand side management is expected to have a significant impact on distribution system, the second step consists of obtaining the distribution networks for the regional cases. The aggregated power profiles of distributed load and generation have been extracted for each primary substation, which serves as the point of common coupling between the high voltage transmission system and the medium voltage distribution network. These power profiles have been separated and spread over the synthetic distribution networks to model the connected loads and generation units at each node. The time series returned by MILES simulations are used to achieve this.

The simulation of the six regional cases requires a variety of datasets that support the simulation of different energy scenarios. In addition to the grid datasets described previously, data related to generation units must also be collected to complement the existing grid models. In addition to Pan-European simulation results described previously, the identification of all necessary power plants required to match the necessary total installed capacities and time-series generation profiles in the FlexPlan project. First, a market analysis is done at the regional level, then the results are used to simulate six regional cases at a more detailed level and create pan-European energy scenarios. The different regional cases require different procedures to complete the identification and allocation of installed capacities. This is due to the quality and availability of previous existing data, such as the grid model received from ENTSO-E for a 2025 scenario. The installed capacities for each target year are pre-given by ENTSO-E scenarios.

For the thermal power plants that will be still operating in 2030, there was a further need to obtain data on the location and installed capacity and to further use this data in order to identify the carbon footprint and air quality impact of these power plants. The simplified air quality model is derived using a Taylor expansion approach based on a full 3D Chemistry and Transport Model (CTM). The CAMx model (Comprehensive Air Quality model), which is capable of reproducing all chemical and physical processes that air pollutants undergo in the atmosphere, is applied together with the DDM algorithm (Decoupled Direct Method for sensitivity analysis in a three-dimensional air quality model). The simulation results in the estimation of sensitivity of air pollutant concentrations to variations in emissions from thermoelectric power plants. This allows for the linking of variations in production of each plant to variations in emissions and, subsequently, pollutant concentrations over fallout areas. Finally, the health impact on the population, as well as the related costs, are derived from the variations in pollutant concentrations. More details on the methodology to obtain the initial network data and environmental impact parameters can be found in **Deliverable 5.1**.

After obtaining the input data, the non-expanded Optimal Power Flow (OPF) is run in order to identify existing congestions and Lagrange Multipliers (LMs) related to the congestions, operational costs including load and generation curtailment costs and other relevant results, which can be used in the pre-processor and grid expansion planning tool. The pre-processor proposes the set of candidates based on the LMs, which are ranked by the congestion severity. This set of proposed candidates is used in solving the grid expansion planning problem by the innovative planning tool. The detailed methodology is presented in *Figure 6.2*.

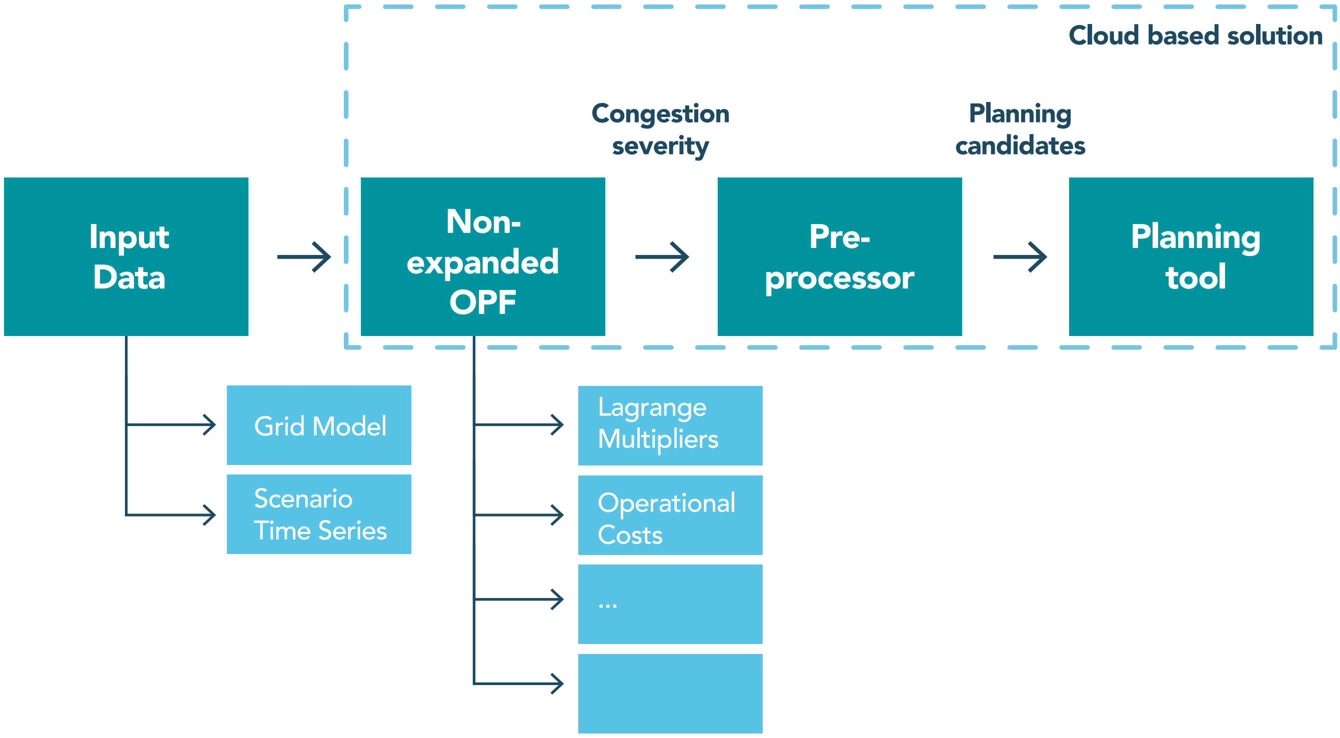



*Figure 6.2 – Workflow of the execution of FlexPlan Regional Case scenarios*

However, the experiments showed that the simulation time for OPF was too high for large-scale test cases. Additionally, the results within the chosen runtime for the tool were not accurate, indicating sub-optimal solutions. As a result, a series of simplification techniques were implemented. The primary objective of the simplifications was to improve the computational efficiency of the grid expansion tool while maintaining the accuracy of the results. The implementation of these simplifications is important, as the results obtained from the tool are not only intended to test the FlexPlan tool, but also to provide realistic results that can impact the role of storage and other flexibility solutions in grid planning, feeding the subsequent development of regulatory guidelines. The simplifications implemented in the grid expansion tool included the application of various techniques to reduce the computational effort required for the simulation. These simplifications are related not only to the reduction of the data to be simulated, which includes simulation of one scenario, i.e. the climate variant with the highest probability, limiting the simulation to four representative weeks and considering aggregation in two-hours time blocks, but also to the simulation in sequence of the three decades (2030, 2040, 2050), to include a limited number of candidates for grid expansion planning, and simplifications related to mathematical description of some models. More details on the aforementioned simplifications can be found in **Deliverable 5.2**.

## 6.2 REGIONAL CASES DEVELOPMENT RESULTS

In light of the computational effort required by the RCs and the simulation time, it is necessary to split the networks for two RCs in order to ensure accurate results: French network is separated from the BeNeLux network and German network is separated from combined Swiss and Austrian network. Additionally, the Northern Countries RC is modelled with a different approach, compared to other RCs: the network data is more focused on Norway due to the availability of more detailed and quality assured network data. The results, presented in **Deliverable 5.2**, demonstrate an analysis of the proposed candidate solutions and their approval status, the change in the costs before and after solving grid expansion planning problem and how it changes throughout the decades.

For most of the RCs the number of congestions increases in each time horizon due to increasing load and generation profiles in the scenarios, combined with the limitation of candidates that are processed in the grid expansion tool, which means that some congestions may not be resolved and transfer to subsequent decades. From *Figure 6.3* and *Figure 6.4* it can be seen how the generation and load curtailment increases in Italian RC from 2030 to 2050, *Figure 6.5* and *Figure 6.6* represent the number and severity of overloaded lines in Balkan RC in 2030, 2040 and 2050.

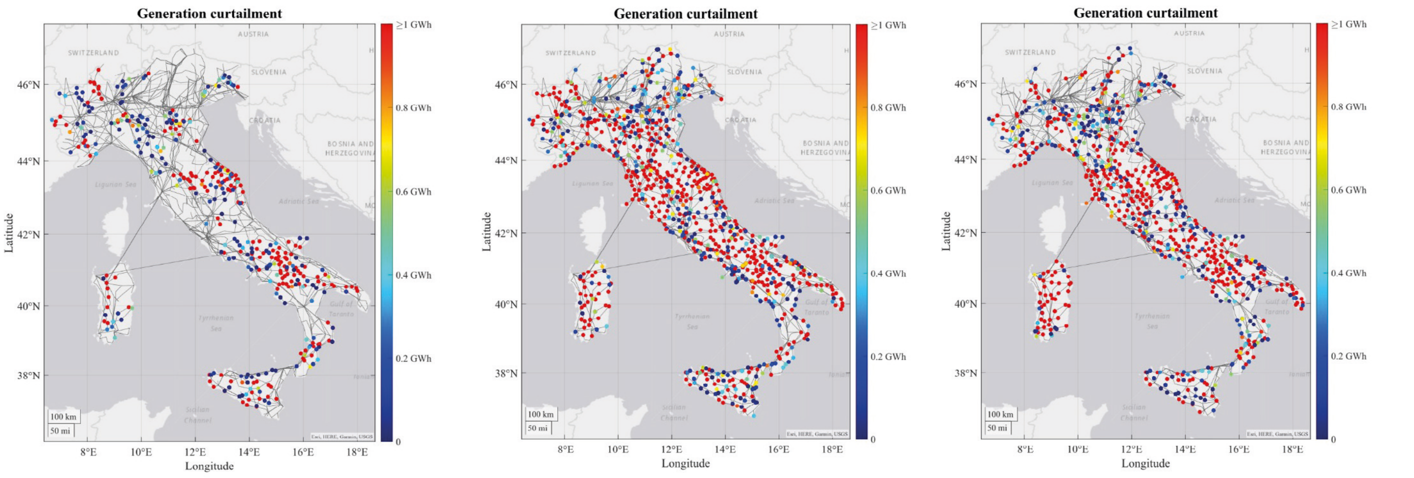



*Figure 6.3 – Generation curtailment in Italian RC for 2030, 2040 and 2050*

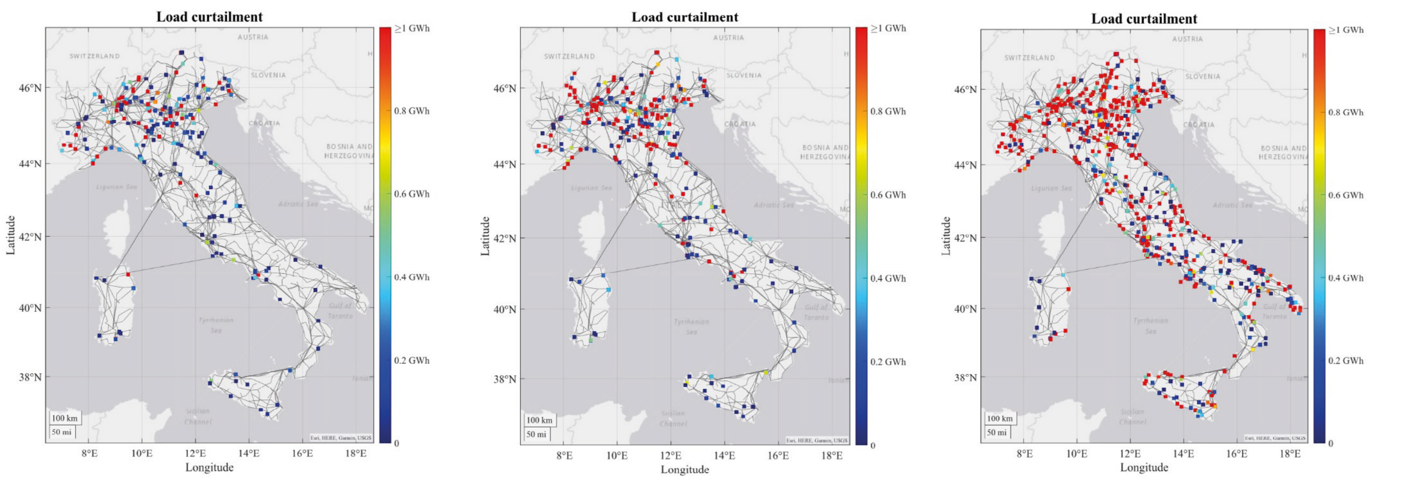



*Figure 6.4 – Load curtailment in Italian RC for 2030, 2040 and 2050*

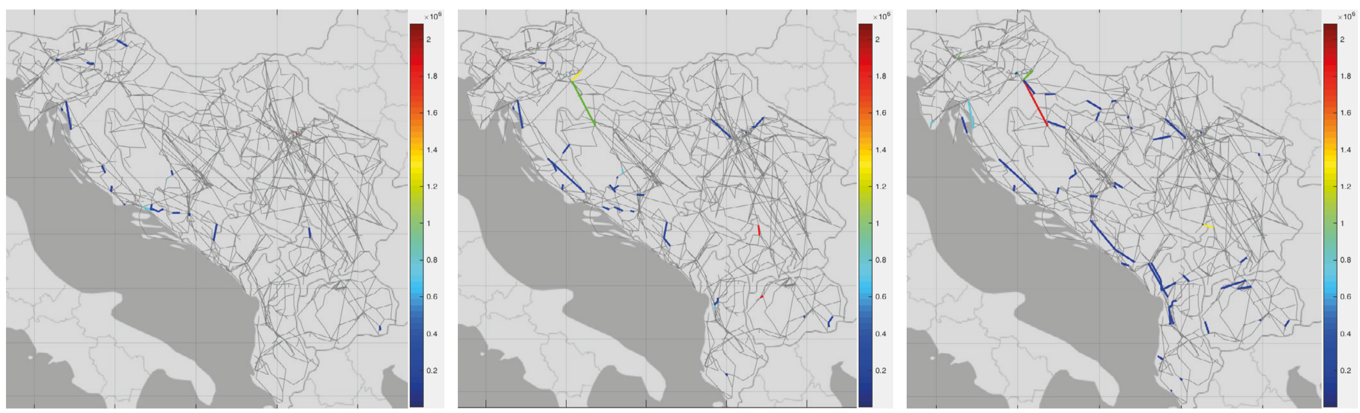



*Figure 6.5 – Overloaded AC branches in transmission in Balkan RC for 2030, 2040 and 2050*

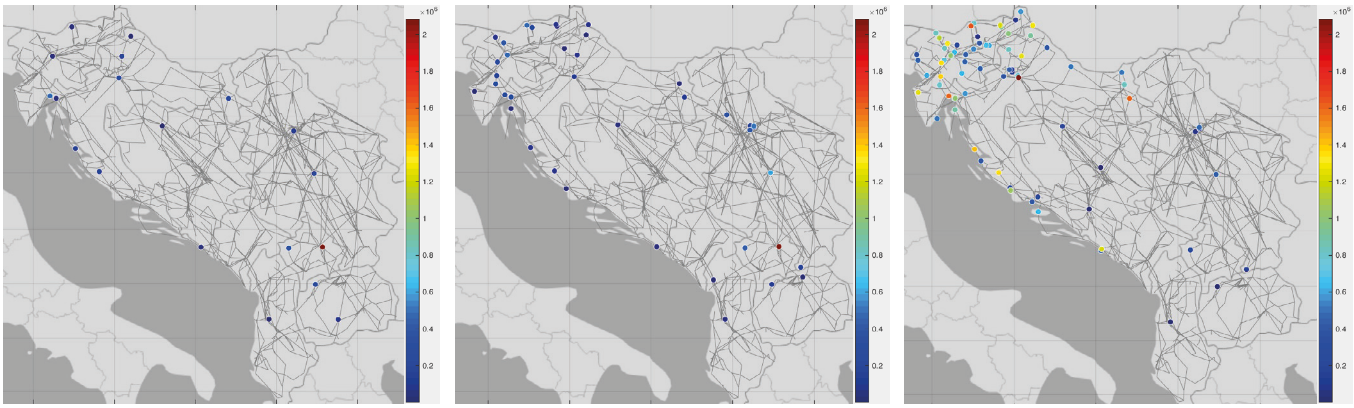


*Figure 6.6 – Overloaded AC branches in distribution in Balkan RC for 2030, 2040 and 2050*

Concerning the number of investment decisions, the number of candidates for traditional grid reinforcement (lines and transformers) in transmission network is lower than in distribution network, however more than 42% of the transmission candidates are approved by the grid expansion tool. The only exception is France, where after manually adding six traditional grid reinforcement candidates in transmission, they are not approved, and nevertheless the congestions are eliminated by distribution candidates locally, along with storages candidates and flexibilization of the load in the congestion site. Regarding the storage and flexibility load candidates, overall there is a trend to increasing the percent of approval of the storage candidates from 2030 to 2040 and from 2040 to 2050, the average percent of approved candidates is 64%.

Additionally, the results for the change in the costs before and after solving the grid expansion problem are analyzed, showing that for most of the RCs the costs increase throughout the decades, which is mainly due to the limiting of number of candidates. However, for BeNeLux regional there is a significant decrease in the costs from 2030 to 2040, as shown in ***Figure 6.7***, which is explained by the fact that the scenario of 2040 forecasts a significant increase in RES generation, whereas the load profile does not increase so drastically, and hence overall the load curtailment costs, which are the main contribution to the total costs in BeNeLux region, decrease in 2040 by approximately 68% comparing to 2030. Nevertheless, for all target years the total costs decreased by investing in the candidates, approved by the grid expansion tool.

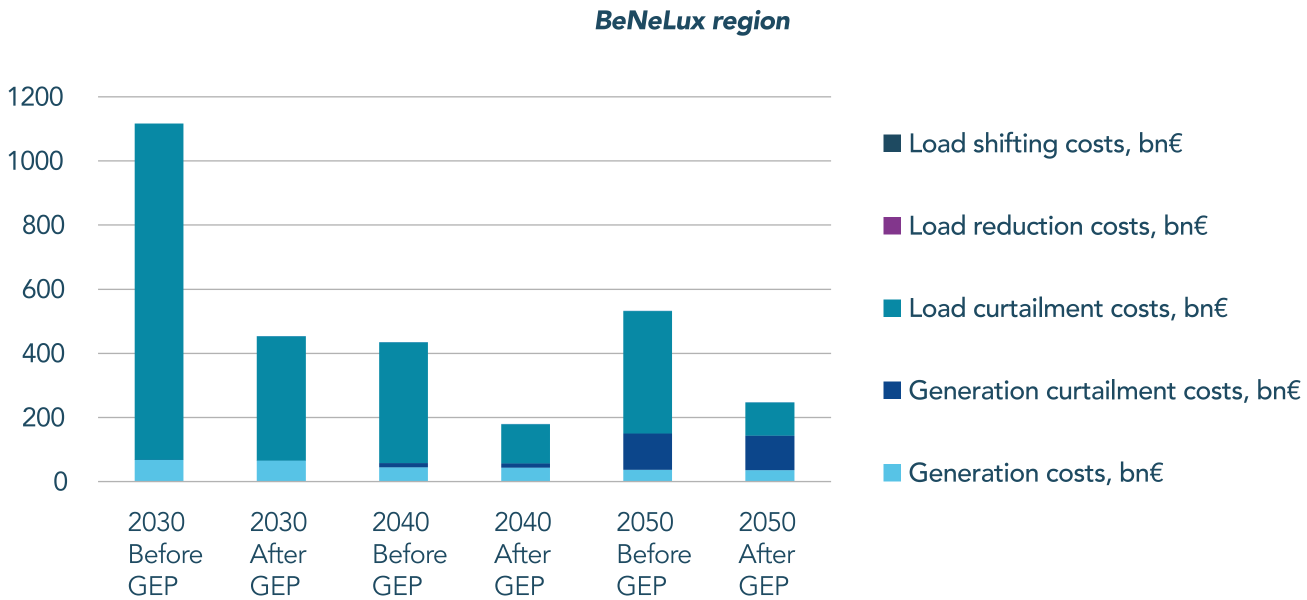



*Figure 6.7 – Total costs in BeNeLux region for 2030, 2040 and 2050 before and after solving grid expansion planning problem*

Also, for Northern Countries RC the total costs in 2040 decreased comparing to 2030, as shown in *Figure 6.8*, because the approved candidates in 2030 decrease significantly the load curtailment and the focused area partially relieved from overloads.

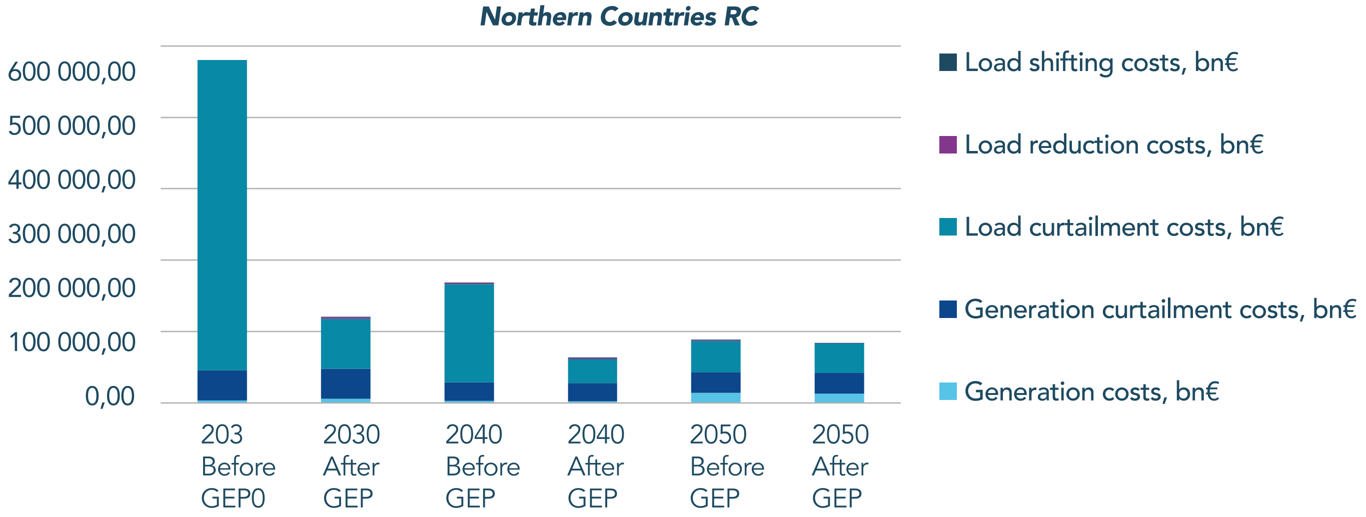



*Figure 6.8 – Total costs in Northern Countries RC for 2030, 2040 and 2050 before and after solving grid expansion planning problem*

With regard to the environmental impact assessment, it is clear that over the years the carbon footprint impact plays a more significant role in the generation costs and the total costs across all RCs comparing to air quality costs.

# 7

# REGULATORY ANALYSIS: HOW TO ENABLE THE FLEXIBILITY RESOURCES FOR NETWORK PLANNING?

The FlexPlan activity dedicated to "Regulatory Analysis" consists of three sub activities, that look into regulatory aspects related to the topics of the FlexPlan project.

## 7.1 ANALYSIS OF THE REGULATORY STATUS QUO AND STRATEGIES IN EUROPE

The first part of the activity was initiated by the beginning of the project and consisted of an assessment of the Pan-European regulatory framework. The intention was to ensure that the project outcomes comply with the overall Pan-European political targets and thereby to set an optimal environment for the real implementation of the planning tool realized by the FlexPlan project.

The first step applied qualitative evaluation methods, based on data collected through literature screening and survey-based research. The activity followed a stepwise approach, which is presented in *Figure 7.1*, where the activity was divided into two parallel streams: one carried out a screening of a set of documents selected by the project group, while another complemented by a reference to the existing practices at both Transmission and Distribution System Operators (TSO and DSO) based on a survey. The survey involved three European TSOs and four DSOs.

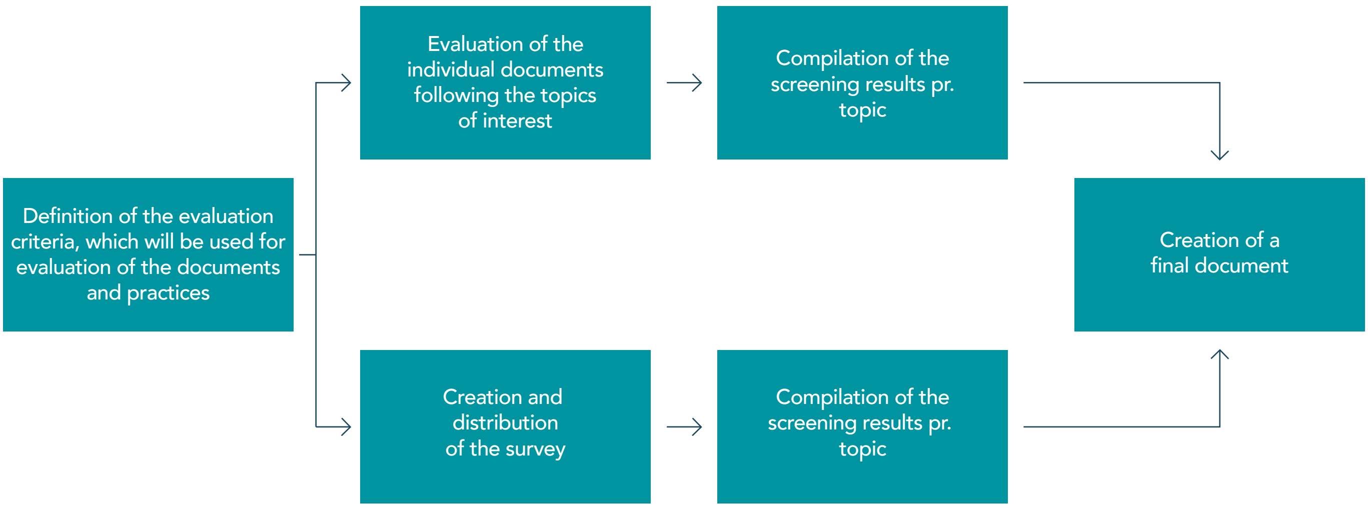



*Figure 7.1 – Steps in the working methodology*

The screening covered a selection of the relevant documents, issued by several types of stakeholders including, including the European Commission (EC), ENTSO-E and the interest organisations representing DSOs. The study focused on a pre-defined selection of issues, which have critical importance for FlexPlan project and are called "topics of interest". These topics represent either some key assumptions that will have to be made within the project activities, or/and some attributes, which can be directly or indirectly decisive for the development and later for the implementation of the project outcomes.

Some of the main conclusions from the analysis of the regulatory status quo and strategies in Europe are presented below.

**Requirements related to consideration of flexible resources in planning**: Summarising the results of the screening process above, the importance of the flexible resources was clearly stated in the Internal Electricity Market (IEM) Directive[16]. The document includes a specific section (Art.32) dedicated to incentives for use of flexibility sources in distribution, stating that the distribution network development plan shall also consider demand response, energy efficiency, energy storage facilities or other resources that the DSO has to use as an alternative to system expansion. Furthermore, the same document defines that when elaborating the Ten-Year Network Development Plan (TYNDP), TSOs shall fully consider the potential for the use of demand response, energy storage facilities or other resources as alternatives to system expansion. The EC Regulation 2019/943 on the internal market for electricity[17], which is linked to the above-mentioned Directive, states that in order to integrate the growing share of renewable energy, the future electricity system should make use of all available sources of flexibility, particularly demand side solutions and energy storage. In ENTSO-E's 3rd Guideline for Cost Benefit Analysis (CBA) of Grid Development Projects[18], flexibility of demand is considered as a consistent part of the estimation of the socio-economic welfare.

The project concluded that there was a clear indication from the present regulatory framework and supported by a broad agreement across different stakeholders that flexible resources should be used as a viable resource for the operation of the power system and thus it should be considered in the planning procedures of the power grid.

**Ownership and operation of energy storage**: The study specifically highlighted the importance of this issue with regards to the establishment of a regulation to support a future planning methodology taking into consideration the role of storage and flexibility in the FlexPlan methodology. The most recent version of IEM Directive presented in 2019 the official position of the EC regarding ownership of energy storage facilities by respectively DSOs and TSOs. The document reaffirmed the position stated in the previous drafts of the Directive, which, as a general rule, does not allow SOs to own, develop, manage, or operate energy storage facilities. However, Art. 54 of the same document refers that SOs are allowed to own, operate or manage such devices, among other conditions, if these devices are "are fully integrated network components and the regulatory authority has granted its approval".

**Rules for allocation of costs and incomes between TSOs and DSOs in new common investment projects**: From the Transmission side, following the requirements of the EU Regulation 347/2013 on guidelines for trans-European energy infrastructure[19], ENTSO-E has developed a CBA of Grid Development Projects, ensuring a common framework for multi-criteria CBA for TYNDP projects. However, there are no commonly agreed rules for allocation of costs between TSOs and DSOs in common investment projects.

The survey results indicated that the present practice is based on a split of costs at transmission system level. However, this practice may be reconsidered in case flexibility resources from distribution networks will be actively employed and coordinated for the provision of system services to TSOs. For that time there was no regulatory framework, applicable to this case.

**Multi-criteria vs. cost-based approach for evaluation of new projects**: The ENTSO-E's 3rd CBA guideline describes the common principles and procedures for performing combined multi-criteria and cost-benefit analysis using network, market, and interlinked modelling methodologies for developing Regional Investment Plans and the EU-wide TYNDP. There are several reasons for selection of this combined approach. It is important to repeat the point made by ENTSO-E in its CBA guideline: costs mostly rely upon scenario-independent factors like routing, technology, material, etc., while benefits are strongly correlated with scenario specific assumptions.

**Costs functions representing reliability in Cost and Benefit Analysis**: The study indicated that the main challenge is to represent reliability in monetary terms. The commonly used key indicator for reliability is the lost load, which is monetised via the Value of Lost Load indicator (VOLL). According to ENTSO-E's CBA guideline the value for VOLL that is used during project assessment should reflect the real cost of outages for system users, hence providing an accurate basis for investment decisions. It is also stated that the experience has demonstrated that estimated values for VOLL vary significantly in dependency of geographic factors, differences in the nature of load composition, the type of affected consumers, and the level of dependency on electricity in the impacted geographical area, differences in reliability standards, the time of year and the duration of the outage.

**Priorities for sharing of resources between TSO and DSO**: The IEM Directive defines that DSOs shall cooperate with TSOs for the effective participation of market participants connected to their grid in retail, wholesale and balancing markets. Delivery of balancing

[16] The European Commission, "Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU,"

[17] The Europeans Commission, "Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity,"

[18] ENTSO-E, "3rd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects," Brussels, 2021.

[19] European Commission, "Regulation (EU) No 347/2013 of the European Parliament and of the Council of 17 April 2013 on guidelines for trans-European energy infrastructure

services stemming from resources located in the distribution system shall be agreed with the relevant TSO.

However, further screening and survey of the present practice indicated that at present there is no common regulatory or practice background allowing to draw clear conclusions on this topic. The necessity of defining this is clearly highlighted both at the institutional level and by the stakeholders.

**Responsibilities for congestion management and balancing**: According to the IEM Directive [4] while performing its main tasks (the efficient, reliable and secure operation of the distribution system), the DSO shall procure the non-frequency ancillary services needed for its system in accordance with transparent, non-discriminatory and market-based procedures, unless the regulatory authority has assessed that the market-based provision of non-frequency ancillary services is economically not efficient and has granted a derogation. According to the same document, TSO is responsible, in that context, for ensuring the availability of all necessary ancillary services, including those provided by demand response and energy storage facilities. Several ENTSO-E's documents, including the 3rd CBA Guideline and "European Power System 2040: Completing the map"[20] clearly presume that responsibility for balancing and congestion management is TSOs' responsibility. Regarding the evolution of roles and responsibilities, in a 10-20 years' timeframe it is reasonable to suppose that TSOs will remain responsible for system balancing and congestion management in their respective networks, while DSOs will be allowed to deal with congestion in their own distribution network.

The first step concluded that there were strong regulatory signals prompting European system operators to consider flexible resources as a new important active subject in the grid expansion planning process for. This strengthened once again the importance and proper timing of FlexPlan project, both for testing new innovative grid planning methodologies coping with the present challenges, for the comprehensive scenario assessment up to 2050 and for the final synthesis of the results into regulatory guidelines brought to the attention of National Regulators and the Commission. The complete results are presented in **deliverable D6.1**.

## 7.2 LEARNINGS FROM THE REGIONAL CASES AND IMPLICATIONS FOR THE REGULATORY PRACTICES

The main goal of the second part in the activity was to analyse the outcomes and learnings from the six regional cases and derive conclusions applicable for the national/regional regulation and practices, which could impose limitations for application of the tool. The secondary goal for the activity was to apply the preceding conclusions in evaluation of replicability and scalability potential for the main outcomes of the FlexPlan project.

### 7.2.1 Regulatory practices in the light of outcomes from the regional cases

Despite the high computational complexity of nodal models including both transmission and distribution (T&D) networks, some already mentioned features of the FlexPlan approach (Benders' decomposition and T&D decomposition) made it possible to retrain the numerical tractability of the models. In particular, the T&D decomposition represents one of the main improvements brought by FlexPlan.

Indeed, the results of the six regional cases, if compared to the present practices highlighted:

- **The importance of the interaction between planning procedure of TSO and DSOs**. Indeed, in many cases it is demonstrated that overall system costs which arises due to the presence of congestions in the transmission system are reduced thanks to the settlement of resources connected to the distribution network.
- **The necessity to use a nodal network model in order to avoid underestimation of the curtailment of renewable energy production**. A zonal approach would provide too optimistic results in systems characterised by high RES penetration and many binding network constraints.

The **Deliverable D6.2** gives a more detailed explanation of the described advantages of the FlexPlan approach, deepening the present regulatory practices and in which ways they should be updated and improved.

[20] ENTSO-E, "European Power System 2040: Completing the map", Available: https://docstore.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/european_power_system_2040.pdf

### 7.2.2 Evaluation of replicability and scalability potential

The assessment of the main outcomes of FlexPlan project was divided into two separate parts:

- The FlexPlan methodology i.e., combination of different methods and techniques assembled together in the project, allowing to make estimations of the optimal system expansion considering use of flexible resources.
- The FlexPlan tool i.e., project-specific implementation of the FlexPlan methodology in a set of software codes and data.

The present study refers to scalability and replicability terms and definitions, which were established in the framework of EU project Grid+ specifically for the SmartGrids domain . These terms and definitions are not novel, but based on several technical studies and modified, whenever it was necessary, in order to function appropriately within the domain.

- Scalability is the ability of a system to maintain its performance (i.e., relative performance) and function, and retain all its desired properties when its scale is increased without having a corresponding increase in the system's complexity.
- Replicability denotes the property of a system that allows it to be duplicated at another location or time.
- A system is understood as a set of interacting elements with similar boundary conditions.

Several other factors should be considered:

- The ability of a system to scale or/and replicate does not necessarily imply that the scaled-up system performs well.
- Scalability is often design-dependent and that it must be tackled from the very beginning.
- Scaling-up and replication might be interlinked, scalability and replicability are independent. The former is rather system dependent, whereas the latter depends on the expected change of the boundary conditions.

Although scalability and replicability of each system depends on specific factors, common and sufficiently generic factors should be sought.

- Technical factors determine whether the solution developed in a particular project is inherently scalable and/or replicable, i.e., whether it is feasible to scale-up and/or to replicate.
- Economic factors reflect whether it is viable to pursue scaling up or replication.
- Regulation and acceptance of stakeholders such as end users, regulators, authorities, etc., reflect the extent to which the current regulatory and social environment is ready to embrace a scaled-up version of a project or whether a new environment is suitable for receiving a project.

The stipulated factors were evaluated separately for the FlexPlan methodology and the FlexPlan tool. In this way the study wanted to assess whether a more refined implementation of the methodology may improve any potential shortcomings identified in the study. The assessment was made, by assigning scores, similar to standard Likert-scale, for each factor and estimation of average values (see the results in FlexPlan D6.2).

In general, the assessment shows very high scalability level, with some minor limitations related to computational power, required for upscaled versions of the tool. At the very same time it must be considered that the accomplished regional studies have already a realistically big scale, covering whole regions and countries. The same applies to replicability potential of both the methodology and the tool. The complete results are presented in **deliverable D6.2**.

## 7.3 REGULATORY GUIDELINES FROM THE FLEXPLAN PROJECT

The third and the final step of the activity provided a comprehensive overview of the present regulatory framework and concludes the analysis by formulating guidelines and recommendations for a proper deployment of flexibility resources. The development of these recommendations is based on the importance of the role of flexibility resources, demonstrated by the FlexPlan tool, and possible regulatory barriers, identified in European and national regulations. The analysis reviewed the previously identified regulatory acts and documents and, starting from the delineated "topics of interest" described in Section 7.1, a total of ten key factors is selected to analyse recent changes in the regulatory landscape and the possible barriers encountered when implementing the FlexPlan methodology in the present EU end national regulatory context.

**Incentives for settling new flexibility resources**: The deployment and development of flexibility resources must be accelerated and guided by means of incentivization mechanisms dedicated to private investors. The incentivizing mechanisms should reflect the identified system needs, supporting the installation of new flexibility resources where the system has shown weakness and bottlenecks, in order to ensure a safe operation of the grid avoiding unnecessary investments.

**Storage ownership and operation**: The main reasons that justify why SOs are not allowed to own and operate storage facilities are 1) the risk for market distortion because network operators are not subjective to competitive pressure as investments are spread across final users; 2) generation of conflict of interests because SOs would act as market participants; 3) part of the resource value would be lost because storages would not be allowed to participate to markets in case they are owned by SOs; and 4) an increase of network tariffs would be expected to cover SOs investments. Anyway, the proved importance of storage facilities in contributing to the security of energy supply drives toward the necessity of new actors which can participate in network investments.

**Responsibilities and data exchange between TSO and DSO in planning**: Some changes in the defined roles and responsibilities of TSO and DSOs are required in order to consider the integration in the framework of DERs and active consumers. A clear regulatory framework should well define where and when responsibilities of TSO end and the ones of DSOs start. Furthermore, guidelines for the cooperation of the network development plans are necessary in order to coordinate planning procedures, grids expansions and development flexibility assets.

**CBA updates and internalization of environmental costs**: The uptake of flexibility resources requires an update of the present CBA approach which should consider every benefit brought by flexibility resources. Two main aspects should be considered while performing a CBA: first the coordination between TSO and DSOs in defining required investment for the network reliability and secondly the monetization of every factors should be strained. In the FlexPlan approach, environmental aspects and carbon-footprint are monetized and a Transmission and Distribution (T&D) decomposition is developed in order to allow a coordinated CBA between different SOs.

**Services that can be provided by flexibility resources: market and non-market dispatch**: The present regulations impose limitations (mainly technical) on the technologies which are allowed to provide flexibility services. To integrate non-conventional flexibility resources many methodologies can be investigated as for example: 1) rules-based approach, modifying the present flexibility resources requirements; 2) dedicated network tariffs, use of Static Time-Of -Use tariffs; 3) connection agreements, to procure flexibility from new providers able to offer the service; and 4) market-based procurement, to acquire short- and long-term flexibility.

**Market flexibility resources can participate in**: Flexibility resources should be allowed to both balancing purposes and congestion management purposes. Demand Side Management (DSM) is a resourceful tool for solving network issues, anyway DSM is not always allowed to participate in electricity markets. In the proposed Guidelines on Demand Response[22] target markets for flexibility resources are mentioned as a possible solution for the integration of flexibility resources in the present regulatory framework. They should be local and allow the participation to all kind of technologies.

**Products tailored for flexibility resource in Realtime-markets**: Some specific markets already exist for the provision of flexibility services, but they mainly include the deployment of conventional technologies. Ad hoc products should be developed looking at what services can be provided by storage facilities and demand response management. For example, the use of block-bids could facilitate the use of resources which are able to move the injection/ejection of electricity from one time-frame to another.

**Regulation on aggregators and possibility to include flexibility in their basket**: Aggregation is a very resourceful process because, not only it reduce the amount of bids on the market, but also favours the integration of resources characterized by small capacities which would not be allowed to participate in the electricity market in other ways. Roles and responsibilities of aggregators are not yet commonly defined at a European level and up to now most of them have been only allowed to participate in pilot projects.

**Interactions with Capacity Markets**: Capacity remuneration mechanisms represent a mean to promote long-term investments. Their structure favours the development of flexibility resources increasing the system reliability. Indeed, capacity remuneration mechanisms could be a viable solution in order to provide incentives for the development of flexibility resources and to assure system operators the availability of flexible resources at a suitable price for congestion management.

**How proposed market reforms could affect flexibility remuneration**: Many market reforms have been proposed in recent years, mainly aiming at monitoring and counteracting the steep increase of energy prices. Anyway, most of them do not distinguish flexibility resources which should be treated separately, taking into account that one of the scopes of these resource is to facilitate network management, thus having as an effect the one of reducing electricity prices.

The activity was concluded by development of a comprehensive set of Regulatory Guidelines, which have already been mentioned in the opening part of the document (see Section: Key Findings). The complete set of results is presented in **deliverable D6.3**.

[20] ACER - Public Consultation on the draft framework guidelnes on demand response

# 8
# WRAP-UP AND WAY FORWARD

After three-and-a-haft years of work within the FlexPlan project, we can state that a first cornerstone has been laid down for the creation of a new grid planning methodology able to cope with some important challenges of the next years: increasing RES penetration, need to provide flexibility for the system, need to coordinate transmission and distribution planning so as to make possible for the flexible resources connected to distribution grids to provide services to the transmission system.

The FlexPlan project has analysed several aspects tied to the synergy between flexibility resources (storage and flexible demand) and grid reinforcement interventions. A new grid planning methodology has been created, a new toolbox applying this methodology has been deployed (as well as a set of open access libraries), regional studies have been developed to demonstrate the feasibility to apply such methodology to problems that have the same level of complexity as those coped with by the System Operators. Finally, the regulatory framework has been analysed, by locating barriers to the application of the FlexPlan methodology and ways to remove them.

What remains to be done?

On one side, the execution of the 6 regional studies mad it necessary to resort to important unnecessary simplifications of the FlexPlan methodology in order to preserve numerical tractability. These simplifications could be removed by using an adequate hardware allowing to parallelize the resolution of the many optimisation models originated by the applied decomposition techniques. However, in order to exploit such parallelization capabilities, a further software development of the toolbox would be necessary too. The producer of the FlexPlan toolbox software, N-SIDE, is already in contact with some System Operators interested to further develop the toolbox in sight of a future application in their grid planning activities. This will also bring to increase the robustness of the FlexPlan toolbox and to make it evolve from a research product towards a full-fledged commercial product. And this is the best proof that what was developed by FlexPlan really met a need of the European System Operators.

Finally, we add a note on the perimeter of the FlexPlan methodology and toolbox, which could easily be expanded to cope with multi-energy systems, so as to study the synergies between energy carriers, the possibility to exploit the linepack of the gas system to provide flexibility for the electricity system, a possible future integration of hydrogen as a separate energy carrier, etc.

# LIST OF PROJECT DELIVERABLES

| TAG | TITLE | DATE |
|---|---|---|
| D1.1 | Monte Carlo scenario generation and reduction | 10/12/2020 |
| D1.2 | Probabilistic optimization of T&D systems planning with high grid flexibility and its scalability | 25/03/2021 |
| D2.1 | Definition and characterization of services to be provided by flexibility elements | 29/06/2020 |
| D2.2 | Flexibility elements identification and characterization | 22/06/2020 |
| D2.3 | Flexibility elements analysis pre-processor simulation tool | 28/06/2021 |
| D3.1 | Planning tool software, including GUI | 08/11/2022 |
| D3.2 | Planning tool user documentation | 26/10/2022 |
| D3.3 | Demo version of the planning tool | 20/12/2022 |
| D4.1 | Pan-European scenario data | 03/08/2020 |
| D4.2 | Pan-European simulation results | 26/03/2021 |
| D5.1 | Data set and planning criteria for the regional studies | 15/09/2021 |
| D5.2 | Grid development results of the regional studies | |
| D6.1 | Guideline for the compliance of network planning tool with EU overall strategies and regulatory conditions | 29/04/2020 |
| D6.2 | Identified regulatory limitations and opportunities based on the regional cases | |
| D6.3 | Lessons and recommendations on pan-European level regulation, policies and strategies | |