

FlexPlan

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

Three scientific papers

D7.4

Distribution Level	PU
Responsible Partner	RSE
Checked by WP leader	Stefania Ballauco (RSE) – WP7 Leader Date: 16/11/2022
Approved by Project Coordinator	Gianluigi Migliavacca (RSE) Date: 16/11/2022



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863819

Issue Record

Planned delivery date	31/03/2023
Actual date of delivery	16/11/2022
Status and version	FINAL

Version	Date	Author(s)	Notes
V1.0	16/11/2022	G. Migliavacca	Generation of the deliverable

About FlexPlan

The FlexPlan project aims at establishing a new grid planning methodology considering the opportunity to introduce new storage and flexibility resources in electricity transmission and distribution grids as an alternative to building new grid elements. This is in line with the goals and principles of the new EC package *Clean Energy for all Europeans*, which emphasizes the potential usage of flexibility sources in the phases of grid planning and operation as alternative to grid expansion. In sight of this, FlexPlan creates a new innovative grid planning tool whose ambition is to go beyond the state of the art of planning methodologies, by including the following innovative features: integrated T&D planning, full inclusion of environmental analysis, probabilistic contingency methodologies replacing the N-1 criterion as well as optimal planning decision over several decades. However, FlexPlan is not limited to building a new tool but it also uses it to analyse six regional cases covering nearly the whole European continent, aimed at demonstrating the application of the tool on real scenarios as well as at casting a view on grid planning in Europe till 2050. In this way, the FlexPlan project tries to answer the question of which role flexibility could play and how its usage can contribute to reduce planning investments yet maintaining (at least) the current system security levels. The project ends up formulating guidelines for regulators and for the planning offices of TSOs and DSOs. The consortium includes three European TSOs, one of the most important European DSO group, several R&D companies and universities from 8 European Countries (among which the Italian RSE acting as project coordinator) and N-SIDE, the developer of the European market coupling platform EUPHEMIA.

Partners



Table of Contents

About FlexPlan 3

Table of Contents..... 4

Executive Summary 5

1 Introduction..... 6

2 Paper 1..... 7

3 Paper 2..... 35

4 Paper 3..... 47

5 Paper 4..... 58

Executive Summary

This deliverable includes three of the most significant scientific papers illustrating the different aspects of the FlexPlan methodology. A fourth paper is added, which provides a thorough description of the T&D decomposition, an original elaboration of the FlexPlan methodology which has interesting characteristics making it very promising for future adoption by the System Operators.

1 Introduction

This deliverable includes three of the most significant scientific papers illustrating the different aspects of the FlexPlan methodology:

- G. Migliavacca, M. Rossi, D. Siface, M. Marzoli, H. Ergun, R. Rodriguez, M. Hanot, G. Leclercq, N. Amaro, A. Egorov, J. Gabrielski, B. Matthes, A. Morch - The innovative FlexPlan grid-planning methodology: how storage and flexible resources could help in de-bottlenecking the European system - *Energies* 2021, 14(4), 1194
- G. Migliavacca, S. Ballauco, H. Ergun, M. Hanot, J. Gabrielski, N. Amaro, A. Morch, R. Rodriguez-Sanchez - The innovative FlexPlan methodology to reap the benefits of including storage and load flexibility in grid planning: methodology and regional study cases - CIGRE 2022 Session
- R. Rodriguez-Sanchez, S. Garcia-Lazaro, G. Migliavacca, D. Siface - Storage and Demand Response inclusion in the network extension planning process - CIGRE Session 2022

The first is a very wide paper illustrating the different aspects of the FlexPlan methodology, the second one provides both an updating of the previous one and a widening of the scope, including the set-up of the regional simulation cases and other aspects. The third is completely devoted to illustrating in detail the methodology of the pre-processor, which is not covered by the first two papers.

Additionally, a fourth paper is added:






- M. Rossi, M. Rossini, G. Viganò, G. Migliavacca, D. Siface, I. Faifer, H. Hergun, I. Bakken Sperstad - Planning of distribution networks considering flexibility of local resources: how to deal with transmission system services - CIREN 2021 Conference

This last paper provides a thorough description of the T&D decomposition, an original elaboration of the FlexPlan project. This algorithm allows both to increase the numeric tractability of the Grid Expansion Problem by allowing to parallelize the optimization of the distribution grids with respect to the one of the transmission grid, and, at the same time, proposes a possible operative scheme for a real interaction between Distribution System Operators and Transmission System Operator within the grid planning by setting a procedure which allows to coordinate the processes of the different System Operators by only exchanging data at the interface between their networks while maintaining privacy on internal data.

After reading the papers above, the reader can grasp the complexity of the methodological elaboration that has been carried out in the FlexPlan project and appreciate the several innovative aspects which could allow the System Operators to upgrade their grid planning procedures in order to keep the pace with the most important challenges that massive RES deployment and the consequent need of system flexibility are posing.

Article

The Innovative FlexPlan Grid-Planning Methodology: How Storage and Flexible Resources Could Help in De-Bottlenecking the European System [†]

Gianluigi Migliavacca ^{1,*}, Marco Rossi ¹, Dario Siface ¹, Matteo Marzoli ¹, Hakan Ergun ², Raúl Rodríguez-Sánchez ³, Maxime Hanot ⁴, Guillaume Leclercq ⁴, Nuno Amaro ⁵, Aleksandr Egorov ⁵, Jawana Gabrielski ⁶, Björn Matthes ⁶ and Andrei Morch ⁷

¹ RSE, via Rubattino 54, I-20134 Milano, Italy; Marco.Rossi@rse-web.it (M.R.); Dario.Siface@rse-web.it (D.S.); Matteo.Marzoli@rse-web.it (M.M.)

² KU Leuven/EnergyVille, Department of Electrical Engineering (ESAT), Kasteelpark Arenberg 10/2445, 3001 Leuven, Belgium; hakan.ergun@kuleuven.be

³ TECNALIA, Parque Tecnológico de Bizkaia, Astondo Bidea, Edificio 700, E-48160 Derio, Spain; raul.rodriguez@tecnalia.com

⁴ N-SIDE, Boulevard Baudouin Ier, 25, B-1348 Louvain-La-Neuve, Belgium; mha@n-side.com (M.H.); gle@n-side.com (G.L.)

⁵ R&D NESTER, Rua Cidade de Goa, n° 4-B-2685-039 Sacavém, Portugal; nuno.amaro@rdnester.com (N.A.); aleksandr.egorov@rdnester.com (A.E.)

⁶ Institute of Energy Systems, Energy Efficiency and Energy Economics, TU Dortmund University, Emil-Figge-Straße 70, 44227 Dortmund, Germany; jawana.gabrielski@tu-dortmund.de (J.G.); bjoern.matthes@tu-dortmund.de (B.M.)

⁷ SINTEF Energi, Sem Saelands vei 11, NO-7034 Trondheim, Norway; Andrei.Morch@sintef.no

* Correspondence: Gianluigi.Migliavacca@rse-web.it; Tel.: +39-320-8395654

[†] This paper is an extended version of our paper published by the 55th International Universities Power Engineering Conference (UPEC 2020): DOI: 10.1109/UPEC49904.2020.9209784.



Citation: Migliavacca, G.; Rossi, M.; Siface, D.; Marzoli, M.; Ergun, H.; Rodríguez-Sánchez, R.; Hanot, M.; Leclercq, G.; Amaro, N.; Egorov, A.; et al. The Innovative FlexPlan

Grid-Planning Methodology: How Storage and Flexible Resources Could Help in De-Bottlenecking the European System. *Energies* **2021**, *14*, 1194. <https://doi.org/10.3390/en14041194>

Academic Editor: Gianfranco Chicco

Received: 2 February 2021

Accepted: 18 February 2021

Published: 23 February 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: The FlexPlan Horizon2020 project aims at establishing a new grid-planning methodology which considers the opportunity to introduce new storage and flexibility resources in electricity transmission and distribution grids as an alternative to building new grid elements, in accordance with the intentions of the Clean Energy for all Europeans regulatory package of the European Commission. FlexPlan creates a new innovative grid-planning tool whose ambition is to go beyond the state of the art of planning methodologies by including the following innovative features: assessment of the best planning strategy by analysing in one shot a high number of candidate expansion options provided by a pre-processor tool, simultaneous mid- and long-term planning assessment over three grid years (2030, 2040, 2050), incorporation of a full range of cost-benefit analysis criteria into the target function, integrated transmission distribution planning, embedded environmental analysis (air quality, carbon footprint, landscape constraints), probabilistic contingency methodologies in replacement of the traditional N-1 criterion, application of numerical decomposition techniques to reduce calculation efforts and analysis of variability of yearly renewable energy sources (RES) and load time series through a Monte Carlo process. Six regional cases covering nearly the whole European continent are developed in order to cast a view on grid planning in Europe till 2050. FlexPlan will end up formulating guidelines for regulators and planning offices of system operators by indicating to what extent system flexibility can contribute to reducing overall system costs (operational + investment) yet maintaining current system security levels and which regulatory provisions could foster such process. This paper provides a complete description of the modelling features of the planning tool and pre-processor and provides the first results of their application in small-scale scenarios.

Keywords: grid planning; grid storage; grid flexibility; demand side management; RES integration; European scenarios; regulatory guidelines

1. Introduction

The most recent agreement among European Union (EU) member states has fixed a binding target of 32% on the share of energy from renewable energy sources (RES) for the year 2030 [1]. 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 [2]. 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, incentivisation procedures should be devised and enforced by regulators also 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 motivate the activity of the FlexPlan Horizon2020 project (<https://flexplan-project.eu/>), which aims at establishing 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 will create a new innovative grid-planning tool whose ambition is 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 will be 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.

Other European past and present research projects tackle grid-planning issues. REALISEGRID (2008–2011, <http://realisegrid.rse-web.it/>) made a first attempt to identify a simple, documentable approach to the technical-economic assessment of alternative investment options in a pan-European perspective.

e-Highway2050 (2012–2015, <http://www.e-highway2050.eu/>) aimed at delivering a modular development plan of the pan-European transmission system till 2050. However, the planning methodology applied by e-Highway2050 only focused on transmission networks and did not consider the grid with nodal detail. While this choice was motivated by the non-in-depth knowledge of network details at a so long-time horizon, the achieved re-

sults could prove too optimistic since many critical constraints were disregarded. Moreover, the expansion strategy leaned upon the expertise of the TSOs for analysing the corridors to be expanded instead of building up a rigorous methodology. Finally, storage and flexibilities were considered in a very simplified way. Environmental externalities (air quality, carbon footprint, landscape constraints) were not considered at all.

More recently, the two projects INTERPLAN (<https://interplan-project.eu/>) and INTERPRETER (<https://www.interpreter-h2020.eu/>) have created sets of tools in support to a wide spectrum of activities, including grid planning. However, none of the project mentioned above sets a methodology to investigate the role of flexibility in grid planning.

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 [3].

The FlexPlan project started in October 2019 and will be completed by September 2022.

The subsequent sections of the present paper aim at providing details on the different on-going project activities, with particular details on mathematic modelling issues, them being the first (and presently most mature) investigations performed within the project:

- Section 2 provides an in-depth introduction to the modelling basis for the innovative planning tool developed by FlexPlan.
- Section 3 details how the pre-processor tool works. Such tool selects a pool of the best candidates for the upgrade of the transmission and distribution systems (refurbishment of existing lines and cables, new storage elements, flexible exercise of big existing industrial and tertiary loads). These candidates are then handed over to the innovative planning tool, which, in turn, selects the best combination among them so as to propose the best expansion path for the system along the three key decades 2030, 2040 and 2050.
- Section 4 clarifies the most important choices which have been made in order to set the reference storylines (scenarios) for the six regional cases and how these cases are connected to the previous solution of the pan-European market models. These latter models are necessary in order to provide a coherent set of border conditions to all six regional cases.
- Section 5 details some preliminary small-scale model implementations which are presently set up in order to check the completeness of the equation set, set a few tuning parameters and test the feasibility of the model decomposition techniques to be then implemented into the planning tool.
- Section 6 provides a few regulatory reflections with respect to the present European regulatory trends so as to highlight the final ambition of the guidelines to be elaborated in the final phase of the project.
- Section 7 includes a few conclusive remarks.

2. An Innovative Planning Tool

The main goal of FlexPlan is to develop and implement a grid expansion optimisation tool able to incorporate flexible grid elements: conventional network assets on the one hand and flexibility sources (such as storage and demand side management) on the other. The tool will be applicable to both transmission and distribution systems, also providing the possibility to optimise investments in both networks at the same time.

Figure 1 shows the structure of the optimisation model and the input parameters. A set of discrete 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 tool. These expansion candidates are characterised both technically and economically by the FlexPlan pre-processor (see Section 3). The installed conventional power generation capacity, RES generation and demand time

series are created by the Model of International Energy Systems (MILES) tool [4], as outlined in Section 4. The required transmission network data is obtained from the Ten-Year Network Development Plan (TYNDP) [5] published by the European Network of Transmission System Operators (ENTSO-E), and distribution network data are obtained by the respective system operators or generated synthetically, e.g., using the DiNeMo tool [6]. The optimisation is carried out in parallel for the three scenarios defined by ENTSO-E TYNDP 2020 [7], whereas yearly climate variants are accounted for in the framework of a Monte Carlo process.

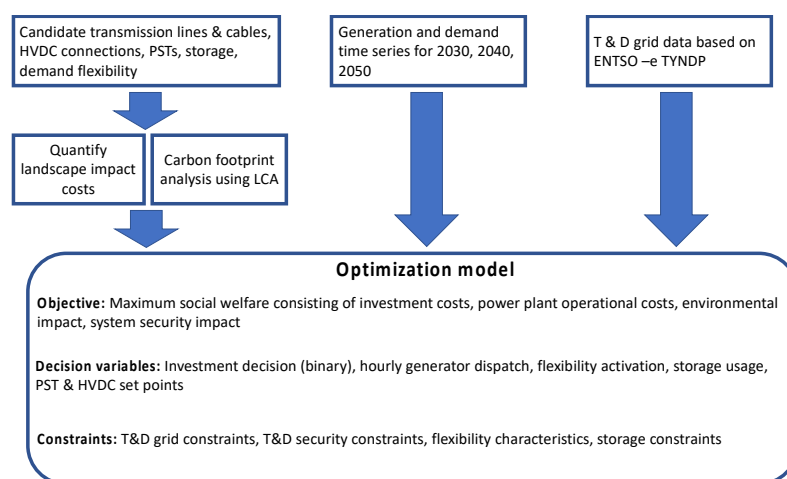


Figure 1. Building blocks, input parameters and output parameters of the planning tool.

2.1. Environmental Modelling

As a first step, grid expansion and flexibility candidates are analysed in order to quantify their costs by also taking into account their CO₂ footprint landscape impact. For all types of candidates used in the planning tool, e.g., AC and DC transmission equipment and battery energy storage, a life cycle analysis is performed to determine their carbon footprint. Thus, CO₂ costs, related to the carbon footprint, are included in the objective function of the optimisation.

Landscape impact-related costs are determined using the optimal transmission routing approach provided in [8]. The optimal routing approach uses spatial weights for installing transmission system equipment in certain areas, in particular existing infrastructure corridors, rural and urban areas, mountain regions and protected natural areas both onshore and offshore. These spatial weights are considered as part of the installation costs, and using an A-star shortest-path algorithm [9], the optimal right of way for each candidate is determined using geographical information. The developed approach is able to deliver optimal routes for both overhead and underground transmission and can provide partial undergrounding solutions [8].

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 is developed, which determines the air quality impact by using the hourly generation dispatch (which is calculated by the optimisation solver), emission properties of generators and their geographical location. Comparing the total annual electricity generation of conventional generators with reference conditions obtained from historical data, the concentration of emissions and their impact on human health are assessed.

In this way, environmental externalities are fully taken into account in calculating the best trade-off between T&D system investments and operational costs.

2.2. Optimisation Objective

The objective of the optimisation is to maximise the system social welfare. This is obtained by minimising the sum of T&D grid investments, operational costs bound to

system dispatch and environmental impact costs, while maximising the benefits achieved by the use of the flexibility sources and storage. The objective function is defined as in Equation (1). In the objective function, the set $y \in S_y$ denotes the planning years within the set {2030, 2040, 2050} and $t \in S_t$ denotes all time points considered in each planning year, e.g., 8670 h. For all generators in the system, $g \in S_g$, dispatching costs are assumed proportional to generated power ($P_{g,t,y}$) and are calculated by using the air quality impact cost per generated MWh ($C_{g,y}^{aq}$), the fuel price (θ_y^f), the CO₂ emission factor (G^{pf}) and the price of CO₂ emissions (θ^{CO_2}). Additionally, a term to penalise renewable energy curtailment is added to the objective function ($C_{g,y}^{res,curt} \Delta P_{g,t,y}^{res}$) to favour renewable generation dispatch.

For all existing and candidate storage assets, $j \in S_j$ and $jc \in S_{jc}$, respectively, the costs associated with injections/absorptions per megawatt-hour are considered. The power demand of each flexible consumption unit, $u \in S_u$, is modelled by including the cost of involuntary demand curtailment ($C_{u,t,y}^{lc}$), the cost of up- and downwards demand shifting ($C_{u,t,y}^{ds}$) and the cost of voluntary energy not consumed ($C_{u,t,y}^{nce}$). The power demand of nonflexible consumption units, $n \in S_n$, can also be curtailed and as such is represented in the objective function with its corresponding cost $C_{n,t,y}^{lc}$. Additionally, nodal power and energy slack terms ($EE_{n,t,y}$ and $LL_{n,t,y}$) are introduced in the objective function in order to avoid infeasible solutions for highly congested hours. These slack terms are penalised with costs much larger than the cost of demand curtailment, $C_{n,t,y}^{EE}$ and $C_{n,t,y}^{LL}$, respectively. A binary investment decision variable α is used for each possible candidate, e.g., storage ($j \in S_j$), demand flexibility ($u \in S_u$), AC power lines and cables ($lc \in S_{lc}^{ac}$), phase-shifting transformers ($bc \in S_{bc}$), high-voltage direct current (HVDC) lines ($dc \in S_{dc}^{dc}$) and HVDC converter stations ($zc \in S_{zc}$). All candidates are represented by their investment cost I , their carbon footprint cost FP^{CO_2} and their landscape impact cost LS .

The optimisation is performed jointly for three target years $y \in \{2030, 2040, 2050\}$, and each year is characterised by a continuous time series of 8760 h, which is necessary for accurate modelling of storage and flexibility activation. As a result, a stepwise investment plan for new grid connections and flexibility investments is obtained. Note that in the presence of multiple possible future scenarios ($s \in S_s$), a stochastic problem is obtained where a trade-off of investments is sought based on the scenario probabilities π_s .

$$\begin{aligned}
 \sum_{s \in S_s} \pi_s \sum_{y \in S_y} \left\{ \sum_{t \in S_t} \left[\sum_{g \in S_g} \left[C_{g,y}^{aq} + \left(\theta^{CO_2} G^{pf} + \theta_y^f \right) \eta_g^f \right] P_{g,t,y,s} + C_{g,y,s}^{res,curt} \Delta P_{g,t,y,s}^{res} \right. \right. \\
 + \sum_{j \in S_j} \left[C_{j,t,y,s}^{abs} P_{j,t,y,s}^{abs} + C_{j,t,y,s}^{inj} P_{j,t,y,s}^{inj} \right] \\
 + \sum_{jc \in S_{jc}} \left[C_{jc,t,y,s}^{abs} P_{jc,t,y,s}^{abs} + C_{jc,t,y,s}^{inj} P_{jc,t,y,s}^{inj} \right] \\
 + \sum_{u \in S_u} \left[C_{u,t,y,s}^{nce} \left(P_{u,t,y,s}^{ref} - P_{u,t,y,s}^{nce} \right) + C_{u,t,y}^{ds} \left(\Delta P_{u,t,y,s}^{ds,up} + \Delta P_{u,t,y,s}^{ds,dn} \right) \right. \\
 + C_{u,t,y,s}^{lc} \left(P_{u,t,y,s}^{min} - P_{u,t,y,s}^{lc} \right) \left. \right] + \sum_{n \in S_n} C_{n,t,y,s}^{lc} \left(L_{n,t,y,s}^{ref} - L_{n,t,y,s}^{lc} \right) \\
 + \sum_{n \in S_n} \left(C_{n,t,y,s}^{EF} EE_{n,t,y,s} + C_{n,t,y}^{LL} LL_{n,t,y,s} \right) \left. \right] \\
 + \sum_{j \in S_j} \alpha_{j,y} \left(I_{j,y}^E \left(E_j^{max} \right) + I_{j,y}^P \left(P_j^{max} \right) + FP_{j,y}^{CO_2} \right) \\
 + \sum_{u \in S_u} \alpha_{u,y} \left(I_{u,y} + FP_{u,y}^{CO_2} \right) + \sum_{lc \in S_{lc}^{ac}} \alpha_{lc,y} \left(I_{lc,y} + FP_{lc,y}^{CO_2} + LS_{lc,y} \right) \\
 + \sum_{dc \in S_{dc}^{dc}} \alpha_{dc,y} \left(I_{dc,y} + FP_{dc,y}^{CO_2} + LS_{dc,y} \right) \\
 + \sum_{zc \in S_{zc}} \alpha_{zc,y} \left(I_{zc,y} + FP_{zc,y}^{CO_2} + LS_{zc,y} \right) \\
 + \sum_{bc \in S_{bc}} \alpha_{bc,y} \left(I_{bc,y} + FP_{bc,y}^{CO_2} + LS_{bc,y} \right) \left. \right\}
 \end{aligned} \quad (1)$$

2.3. Network, Demand and Storage Modelling

Considering the three target decades and the detailed characterisation of each planning year, a large-scale mixed-integer problem optimisation is obtained. The power flow equations and technical constraints for flexibility sources and storage are formulated in a linear way in order to maintain tractability of the model, notwithstanding its huge dimensions.

To make the model applicable to both transmission and distribution networks, the underlying network model is decomposed in two components, namely the meshed and the radially operated networks. This distinction is made independent of the juristic definition of transmission and distribution networks, as these are significantly differing among 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. Therefore, a generic AC branch model is used in the optimisation model, which is then parameterised according to the specifics of the modelled equipment. The possibility of expanding the system with point-to-point and meshed HVDC connections is considered according to [10,11]. 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. The transmission network constraints are formulated using a linearised power flow formulation and consist of nodal power balance constraints, Ohm's law over existing and candidate branches, DC node power balance equations, Ohm's law over DC existing and candidate branches and active power flow limits of existing and candidate branches.

As the modelling of all radially operated systems would result in an unmanageable problem size, the distribution optimisation problem is decomposed from that of the transmission: the expansion of distribution networks is solved first and considered as a planning candidate for the meshed system. For this purpose, a four-step approach is chosen. In step one, the optimal expansion plan of the radial network is determined with the objective of solving only local congestion in the most economical way. This marks the least-cost expansion option for the radial network. For the obtained grid expansion solution, the maximum upwards and downwards flexibility which can be provided towards the meshed transmission system can be calculated using two separate optimal power flow calculations, having the following objective functions:

$$\min \sum_{y \in Y} \sum_{t \in y} P_{l,t,y}^{fr} - \sum_{y \in Y} \sum_{t \in y} \sum_{j \in S_j} P_{j,t,y}^{inj} - \sum_{y \in Y} \sum_{t \in y} \sum_{j \in S_{jc}} P_{j,t,y}^{inj} \quad (2)$$

$$\max \sum_{y \in Y} \sum_{t \in y} P_{l,t,y}^{fr} + \sum_{y \in Y} \sum_{t \in y} \sum_{j \in S_j} P_{j,t,y}^{abs} + \sum_{y \in Y} \sum_{t \in y} \sum_{j \in S_{jc}} P_{j,t,y}^{abs} \quad (3)$$

where $P_{l,t,y}^{fr}$ is the active power flow from the transmission network to the radial network and $P_{j,t,y}^{inj}$, $P_{jc,t,y}^{inj}$ and $P_{j,t,y}^{abs}$, $P_{jc,t,y}^{abs}$ are the power injections and absorptions of existing ($j \in S_j$) and candidate storage ($jc \in S_{jc}$) devices (belonging to the considered distribution network, respectively).

In step two, the same optimisation is performed with the objective of providing the maximum amount of flexibility in terms of delivering and absorbing active power to/from the meshed network. This option marks the highest-cost expansion option of the radial system. For this purpose, all candidates on the distribution system are considered to be invested in and the range of upwards and downwards flexibility is calculated using the optimal power flow approach, as previously described.

In an optional third step, the optimal expansion of the radial networks with intermediary flexibility requirements can be determined, e.g., as a set of different combinations of selected candidates, for which again the maximum upwards and downwards flexibility range is determined. In this way, a set of flexibility levels are obtained with their corresponding cost of radial system expansion. Eventually, in the fourth step, these radial grid

expansion options are provided as a set of discrete expansion candidates for the meshed system, modelled as a generic source of flexibility injecting/absorbing power into/from the meshed network, considering technical limits obtained as outcomes of the previous steps. As a consequence, the best trade-off between the flexibility level of the radial network and the expansion costs of both the radial and meshed networks is considered. As, due to the decoupling described above, the expansion problem for the radial systems can be performed independently from the meshed system, the optimisation problem can be solved much more efficiently. To account for the reactive power and voltage drop in the radial network, the linearised branch flow formulation [12] has been used to represent the power flow equations.

The flexible demand model includes three main components and is defined as

$$P_{u,t,y}^{flex} = P_{u,t,y}^{ref} - \Delta P_{u,t,y}^{nce} + \Delta P_{u,t,y}^{ds,up} - \Delta P_{u,t,y}^{ds,dn} - \Delta P_{u,t,y}^{lc} \quad (4)$$

where $P_{u,t,y}^{flex}$ is the flexible demand defined for each consumer u at each time point t of each planning year y . $P_{u,t,y}^{ref}$ refers to the expected reference demand of consumer u , $\Delta P_{u,t,y}^{nce}$ is the consumer's voluntary demand reduction and $\Delta P_{u,t,y}^{ds,up}$ and $\Delta P_{u,t,y}^{ds,dn}$ are upwards and downwards demand-shifting actions performed by the consumer, respectively. $\Delta P_{u,t,y}^{lc}$ is the involuntary demand curtailment and is used to quantify the power system security-related costs, as some outages in the network may lead to supply interruptions. The amount of voluntary demand reduction is limited via $0 \leq \sum_{t \in S_t} \Delta t \cdot \Delta P_{u,t,y}^{nce} \leq \alpha_u E_{u,y}^{nc,max}$, where $E_{u,y}^{nc,max}$ is the total annual energy not consumed and α_u is the binary investment decision variable for demand flexibility. For demand shifting, the energy consumption over a given period τ needs to be balanced, e.g.,

$$\sum_{t \in \tau} \Delta P_{u,t,y}^{ds,up} = \sum_{t \in \tau} \Delta P_{u,t,y}^{ds,down} \quad (5)$$

and upwards and downwards demand-shifting actions can only be performed for a limited short amount of time τ_u^{grace} :

$$0 \leq \Delta P_{u,t,y}^{ds,up} \leq \Delta_{u,t,y}^{ds,up,max} - \sum_{\tau \in \{t - \tau_{u,y}^{ds,up,grace}, \dots, t-1\}} \Delta P_{u,\tau,y}^{ds,up} \quad (6)$$

$$0 \leq \Delta P_{u,t,y}^{ds,dn} \leq \Delta_{u,t,y}^{ds,dn,max} - \sum_{\tau \in \{t - \tau_{u,y}^{ds,dn,grace}, \dots, t-1\}} \Delta P_{u,\tau,y}^{ds,dn} \quad (7)$$

To complete the planning model, a generic storage model is used to represent different technologies:

$$E_{j,y}^{max} x_{j,t,y} = E_{j,y}^{max} x_{j,t-\Delta t,y} + \Delta t \cdot \left(\eta_{j,y}^{abs} P_{j,t,y}^{abs} - \frac{P_{j,t,y}^{inj}}{\eta_{j,y}^{inj}} + \zeta_{j,t,y} - v_{j,t,y} \right) \quad (8)$$

where $E_{j,y}^{max}$ is the maximum energy capacity of the storage system j and $x_{j,t,y}$ is the state-of-charge at each time point t of each planning year y . $P_{j,t,y}^{abs}$ is the power absorbed from the network, and $\eta_{j,y}^{abs}$ is the absorption efficiency. $P_{j,t,y}^{inj}$ and $\eta_{j,y}^{inj}$ correspond to power injected into the grid and the injection efficiency, respectively. $\zeta_{j,t,y}$ and $v_{j,t,y}$ represent the external energy in and outflows into the storage system, respectively, e.g., natural inflow of water into hydro storage or self-discharge of battery storage. The maximum energy capacity, power injection and absorptions are bound using the binary decision variable $\alpha_{j,y}$ for storage systems:

$$E_{j,c,y}^{min} \alpha_j \leq E_{j,c,y}^{max} x_{j,c,t,y} \leq E_{j,c,y}^{max} \alpha_{j,y} \quad (9)$$

$$0 \leq P_{jc,t,y}^{abs} \leq \alpha_{j,y} P_{jc,y}^{abs,max} \quad (10)$$

$$0 \leq P_{jc,t,y}^{inj} \leq \alpha_{j,y} P_{jc,y}^{inj,max} \quad (11)$$

2.4. Reliability Modelling

The reliability impact of the chosen grid expansion candidates is modelled using the approach illustrated in Figure 2 and is added to the objective function as an additional cost of energy not served, C_{ENS} . Considering a number of critical contingencies, $c \in S_c = \{c_1, \dots, c_n\}$, the cost related to possible power curtailment due to a contingency, $\Delta P_{u,c,t,y}$, is calculated for each demand unit using the value of lost load, $C_{u,t,y}^{voll}$. These costs are summed up over all demand units $u \in S_u$, each time point $t \in S_t$, each planning year $y \in S_y$ and each contingency $c \in S_c$ and are weighed with the contingency probability $\tilde{U}_{c,y,t}$, which is determined by using the failure rate and the mean time to repair (MTTR) of the specific equipment and multiplied by the duration of the contingency Δt . As such, the total cost of reliability is obtained as the weighted sum of the cost of energy not served over the planning horizon. As the power curtailment $\Delta P_{u,c,t,y}$ needs to be calculated for all considered contingencies and this increases the dimensionality of the problem, only a limited number of critical contingencies can be considered.

$$C_{ENS} = \sum_{y \in S_y} \sum_{t \in S_t} \Delta t \cdot \sum_{c \in S_c \setminus \{0\}} \tilde{U}_{c,t,y} \sum_{u \in S_u} C_{u,t,y}^{voll} \cdot \Delta P_{u,c,t,y}$$

Figure 2. Reliability modelling within the FlexPlan model.

2.5. Monte Carlo Scenario Generation and Reduction

The time series input data for the planning tool is created using the MILES simulation framework [4] (see Section 4). As input for the MILES framework, first a database of historical data on demand, wind speed, solar irradiation and hydro generation is created over the past 40 years. For this purpose, Renewables Ninja [13–15] and the ENTSO-E market modelling data [16,17] have been used as the main sources of data. Based on historical data, and macro-scenarios regarding total energy demand and installed power plants capacities, the MILES simulation platform is able to calculate 40 time series of nodal renewable generation and demand with an hourly resolution for a full planning year (8760 h). These time series data are generated for the three planning years considered in

the planning tool, namely 2030, 2040 and 2050. Figure 3 provides a schematic view of the results of the Monte Carlo scenario generation process. The spatial resolution of the generated time series data is based on NUTS-2 regions [18]. A more detailed description of the scenario generation process can be in Section 4.3.

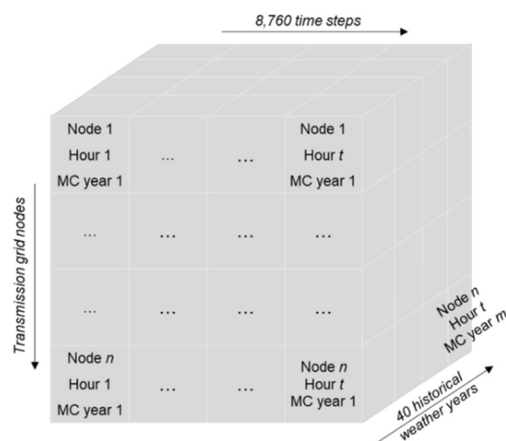


Figure 3. Schematic view of the results of the Monte Carlo scenario generation [15].

As shown in Figure 3, for each planning year, 40 different yearly time series are obtained based on the historical data. As not all time series can be accommodated in the planning tool, due to computational limitations, a scenario clustering methodology is applied. The scenario reduction methodology uses clustering techniques based on feature reduction to reduce the length of the time series on the one hand and *k*-means clustering [19] to reduce the 40 time series to a specified number of clustered time series usable in the planning tool on the other. The feature reduction can be performed by means of principal component analysis (PCA) [20] or by means of clustering different time points based on their characteristic features, such as total demand, total renewable generation, maximum demand variation between time steps and so on.

2.6. Further Improvement of the Computational Efficiency Using Benders Decomposition

Whereas directly solving the original mixed-integer stochastic model incorporating all Monte Carlo scenarios would be numerically too challenging because of high dimensionality, conversely, solving each Monte Carlo scenario separately would result in different investment decisions for each scenario run. Therefore, it is of paramount importance to select an efficient decomposition technique allowing to solve the original stochastic problem, while allowing to decouple it into a number of simpler optimisation problems. That is accomplished in a very efficient way by the Benders decomposition methodology.

In this paper, it is out of scope to present a rigorous introduction to the Benders decomposition technique; as such, we limit ourselves to highlighting how the decomposition is carried out and how an iterative process is derived which converges to the solution of the original stochastic problem. An example of this approach can be found in [21].

As explained by the conceptual scheme in Figure 4, the Benders decomposition technique makes it possible to split the original target function of the stochastic problem into several optimisation problems. The first one, which is denominated upper problem, calculates an optimum value for the integer investment decision variables $\vartheta_{l,y}$, where *l* is the current line or storage device candidate and *y* is the current grid year *y* (2030, 2040, 2050).

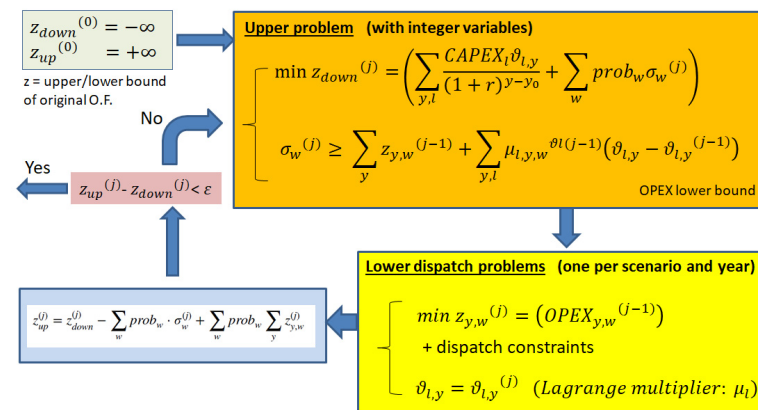


Figure 4. Conceptual scheme of the application on Benders decomposition.

The upper problem is supported by a set of lower problems, each calculating the optimal dispatch for a given Monte Carlo scenario w and a given grid year y . Lower problems themselves contain no integer variables, but they assume that each decision variable $\theta_{l,y}$ is retained at the value decided by the last (j -th) iteration of the upper problem. This is imposed by means of a set of equality constraints $\theta_{l,y} = \theta_{l,y}^{(j)}$ for which the relevant Lagrange multiplier is calculated, too ($\mu_{l,y,w}$). The upper problem, by contrast, is solved by approximating the portion of the original stochastic target function related to the dispatch cost of each scenario (weighed by means of its own probability $prob_w$) with a term σ_w . This latter term is defined as a sum of the dispatch value calculated by the lower problems for scenario w at the time step ($j - 1$) ($Z_{y,w}^{(j-1)}$) and an innovation term which considers the impact on the target function for each decision variable $\theta_{l,y}$ which changes with respect to the previous iteration by means of its own Lagrange multiplier ($\mu_{l,y,w}$).

The Benders iterative process is initiated by setting the two parameters Z_{down} and Z_{up} , providing an upper and a lower bound on the approximation of the original target function. These two variables, which initially take the values of, respectively, minus and plus infinite, are then modified at each iteration as follows:

- Z_{up} takes the optimal value of the upper target function.
- Z_{down} is calculated as the portion only related to investment costs of the upper target function increased by the sum of the last optimal dispatch values calculated by the lower problems ($Z_{y,w}^{(j)}$) weighed each with the probability of the relevant scenario ($prob_w$).

The two values Z_{up} and Z_{down} are expected to get closer during the iterations. When their difference is less than a pre-established threshold ϵ , the iterations are stopped.

3. Analysing the Candidates for Network Expansion

To support the planning process, the FlexPlan project develops a specific software tool which performs a pre-selection of candidates for network expansion. Such tool acts as a pre-processor of the planning tool described in the previous section, and its main objective is to restrict the number of possible network expansion options and, in this way, limit the size of the optimisation problem to be solved.

The flexibility resources analysis is performed through the following steps:

- Network branches potentially affected by congestion are identified on the basis of an optimal power flow (OPF) simulation carried out on a network characterised by the final generation and load scenario for the target year under study (2030, 2040 or 2050) but still before new grid investments are carried out. A ranking of congested lines is proposed based on Lagrange multipliers' (LM) values associated to transit constraints equations for the system tie-lines.
- The flexibility resources analysis tool (pre-processor) proposes a list of network expansion candidates, including storage, demand response (DR), phase-shifting trans-

formers (PSTs) and lines/cables/transformers, to solve congestion in the identified branches. This selection is performed based on congestion characteristics and on possible location-related constraints. Cost and size details are provided related to the technology of each selected candidate.

- Eventually, the proposed candidates for grid congestion support are provided to the planning tool as input, which, in turn, assesses the best planning option for the power system in the time frame of the study.

The interaction between planning tool and pre-processor is shown graphically in Figure 5. Three loops are necessary in order to carry out the complete planning process so as to cover all three target years. The first step is to run an OPF simulation on an electricity network model for the non-expanded scenario of the first year of study, 2030. With the LMs resulting from the OPF and additional information on network nodes characteristics, the pre-processor provides a set of candidates for network expansion for year 2030. Then, the planning tool runs the optimisation process, and the resulting network becomes the non-expanded model for 2040, and it will be the input for the second loop. In the final step, the planning tool will provide the optimal network expansion for the whole period under study (2030 to 2050).

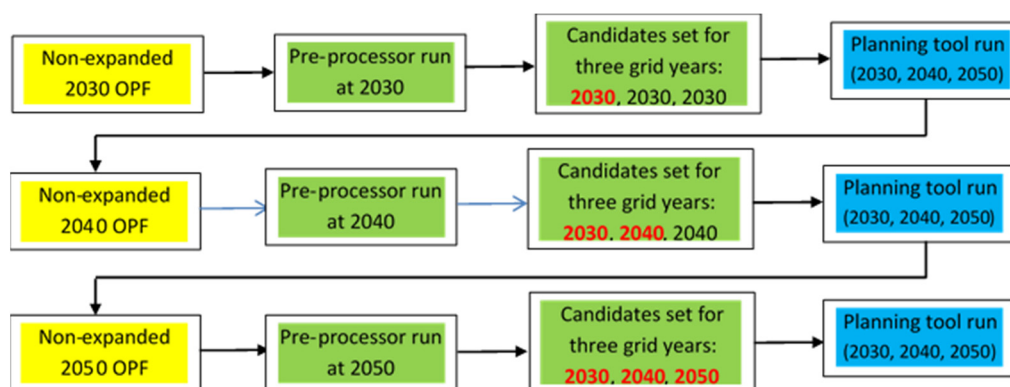


Figure 5. Interaction between planning tool and pre-processor.

The pre-processor methodology starts with the identification of the congested branches in the non-expanded network when a specific scenario is considered. The LMs of line transit constraints, resulting from solving the OPF problem, are the first input for the pre-processor. Their value represents the system dispatching cost reduction, which could be achieved as consequence of a unit increase of the line power flow limit.

The yearly average of LMs throughout a year and the number of congestion occurrences are both used to select the most congested lines in the system.

Once the most congested branches are identified, candidates are evaluated for those locations. The following technologies are considered as candidates to relieve congestions:

- Storage: batteries (lithium ion, NaS and flow), hydrogen, hydro, compressed air storage and liquid air storage
- Demand response: flexible loads
- Conventional network assets: lines, cables and transformers
- Phase-shifting transformers (PSTs)

All the technologies above can be considered as candidates; however, in all cases, locational constraints and bus characteristics are checked. The network information provided for relevant nodes is used to discard, or not, some of the candidate technologies: urban substations, restricted areas, the unavailability of water or caverns or the inexistence of flexible loads, for example, already make unfeasible some of the technologies.

The characteristics of the congestion, such as the number of congestion hours in one year or the number of consecutive congestion hours, make some technologies more appropriate than others. For example, if congestion tends to last more than six hours,

batteries or demand response strategies might not be the best flexibility candidates. These types of rules are to be defined by the pre-processor.

Once the most suitable technologies have been selected, the pre-processor provides a size and cost for each of them. In the case of the size, more than one value can be provided so that the planning tool chooses the best one among them.

Lines and PSTs require additional care.

In the case of lines, if the power flow capacity between two nodes is increased in order to remove congestion (e.g., by reinforcing a given line), transits increase in some portions of the system, and this could recreate congestion elsewhere, even in lines which showed no congestion before the reinforcement was carried out. Lines which could saturate in the chain should be clusterised to create what is generically referred to as an expansion corridor. This is especially relevant for meshed networks. To avoid that some investments turn out ineffective since congestion is just moved from some lines to others, we suppose the influence of nodal injections on line transits can be described by means of the so-called power transfer distribution factors (PTDFs) and that such factors don't change significantly for small reinforcements of the system. PTDFs are used to check how the increase in capacity in one line affects the saturation in other lines.

Given a congested line lc , we consider an injection of power in node K_1 and the same extraction of power in K_2 (see Figure 6) and that the lines power constraints are relaxed so that line transits can go over the rated capacity of the line.

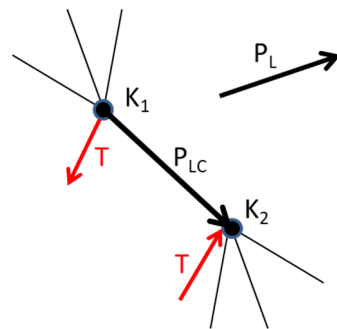


Figure 6. Power transfer distribution factor (PTDF) analysis approach.

Following the definition of PTDFs, we calculate the power flow modification as result of this new power exchange (T), in both the congested line (lc) and a generic line l :

$$P_l - P_l^0 = T(PTDF_{K_2,l} - PTDF_{K_1,l}) \quad (12)$$

$$P_{lc} - P_{lc}^{max} = T(PTDF_{K_2,lc} - PTDF_{K_1,lc}) \quad (13)$$

From those two equations, we eliminate T and put in the relationship the power flow of lc with the power flow of l .

$$P_{lc} - P_{lc}^{max} = \frac{(PTDF_{K_2,lc} - PTDF_{K_1,lc})}{(PTDF_{K_2,l} - PTDF_{K_1,l})} (P_l - P_l^0) \quad (14)$$

When the power flow in l reaches its maximum capacity (i.e., $P_l = P_l^{max}$), at this stage, the power flowing in lc reaches the value P_{lc}^* (see Figure 7):

$$P_{lc}^* - P_{lc}^{max} = \frac{(PTDF_{K_2,lc} - PTDF_{K_1,lc})}{(PTDF_{K_2,l} - PTDF_{K_1,l})} (P_l^{max} - P_l^0) \quad (15)$$

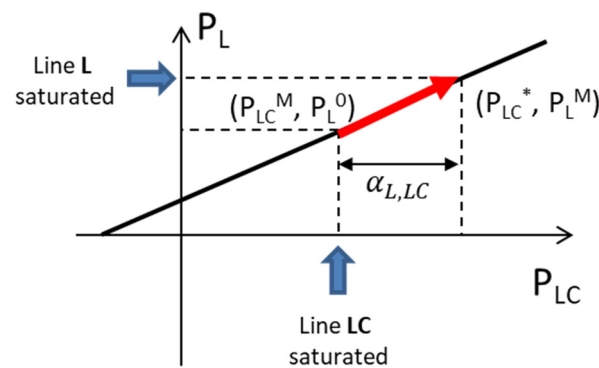


Figure 7. Relationship between the saturation of the congested line and other lines.

Then, we define the parameter $\alpha_{l,lc}$, which represents the oversaturation in line lc when line l gets saturated.

$$\alpha_{l,lc} = \frac{P_{lc}^* - P_{lc}^{max}}{P_{lc}^{max}} = \frac{(PTDF_{K_2,lc} - PTDF_{K_1,lc}) (P_l^{max} - P_l^0)}{(PTDF_{K_2,l} - PTDF_{K_1,l}) \frac{P_{lc}^{max}}{P_l^{max}}} \quad (16)$$

The lines with a higher risk to become congested are those with lower values of $\alpha_{l,lc}$. They should be expanded alongside lc . In this way, an expansion corridor is created.

After all line candidates for grid expansion are selected, the pre-processor interacts with the planning tool (see Section 2), which is, in turn, going to select the best route and technologies to connect two substations, considering landscape characteristics, existing routes, etc. The pre-processor provides the planning tool with the cost and technical characteristics of all candidate lines.

In the case of a PST, this technology provides a controllable phase shift on a grid line so as to move a portion of its power flow to other paths in parallel to that. To understand the impact of the PST on other lines, phase-shifting distribution factors (PSDFs) are used. These factors show the power flow modifications through the grid branches taking place when the PST introduces a unitary increase in the voltage angle between two nodes. In this way, the effectiveness of the solution can be preserved, while avoiding creating congestion in other lines located in the same area.

Finally, whereas the pre-processor proposes new candidate lines through the identification of congested connections, it does not provide line candidates between substations which are not already directly connected in the non-expanded scenario. As a matter of fact, proposing new routes requires an in-depth knowledge of the physical characteristics of the interested territory as well as great experience on the operation of the specific electricity system. However, the FlexPlan planning tool allows the users to propose new connection paths between whichever pairs of nodes. These new connections are automatically considered by the optimisation problem as line candidates for network expansion.

The following Figure 8 summarises graphically the steps carried out by the pre-processor, as well as its input and output.

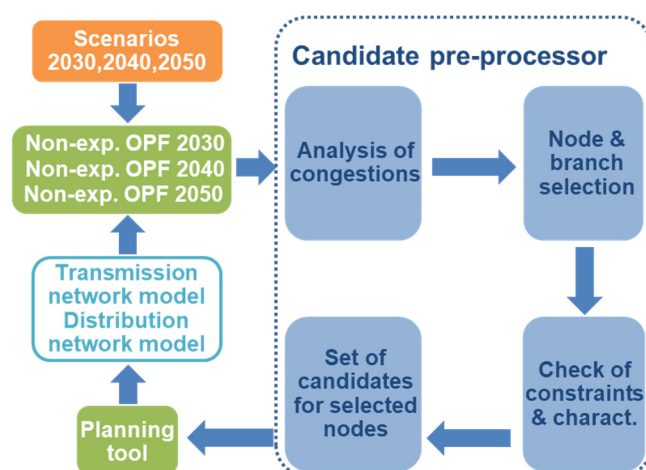


Figure 8. Steps by the flexibility candidate pre-processor.

4. An Ambitious Scenario Analysis Supporting a Long-Term Planning View

FlexPlan aims to design, implement and validate an innovative and ambitious grid-planning tool. The validation of this tool is performed through six ambitious regional cases covering almost all Europe. The creation of these regional cases involves complex data collection and processing activities, putting together energy scenarios for the three target years, geo-referenced transmission and distribution grid models and complementary information for environmental impact studies. The scenarios contain data at the national level (installed capacities, load, commodity prices, net transfer capacities (NTCs)), which, in a second step is cascaded down to the regional/zonal level and then to the nodal level to correspond to grid node details. Furthermore, to ensure a coherent approach between the six regional cases (establishing border conditions between the cases), pan-EU-level datasets are used for the creation of scenarios to be simulated and grid models. The next sections illustrate the workflow of FlexPlan in the preparation of the main datasets required to perform the simulation of the six regional cases.

4.1. Preparation of the Pan-EU Model

Performing the envisaged simulations for the six regional cases aiming at validating the FlexPlan tool requires the existence of a comprehensive data model, which is composed of heterogeneous data from multiple data sources. The data model needs to include:

- Pan-European scenarios to be simulated (load and generation time series);
- Grid models: including transmission and distribution grids at the regional case level; and
- Complementary data: including those to study the impact on landscape, air quality and carbon footprint of selected grid expansion candidates.

4.1.1. Pan-European Scenarios

The three FlexPlan studied scenarios are derived from major political drivers in coherence with ENTSO-E TYNDP 2020 [7], providing a common dataset to be used by all regional cases. These three scenarios provide different future possibilities for the power system, aiming at achieving the climate targets set up by the European Commission. For the purpose of simplicity, FlexPlan reuses the original names, as indicated by ENTSO-E in the TYNDP2020 for these scenarios, which are National Trends (NT), Global Ambition (GA) and Distributed Energy (DE). The NT scenario reflects the most recent EU member state national energy and climate plans (NECPs), submitted to the European Commission in line with the requirement to meet current European 2030 energy strategy targets. On the other hand, DE and GA scenarios are more ambitious and are fully in line with the targets of the Conference of the Parties COP 21, providing different pathways reducing EU-28 emissions

to net zero by 2050. These two scenarios differ only on the technologies to reach the same climate target goals.

These scenarios were created by resorting to data from TYNDP 2020, complemented with TYNDP 2018 [5] and Mid-term Adequacy Forecast (MAF) 2018 [22], also issued by ENTSO-E, when TYNDP 2020 does not contain the required data. However, these reports only provide national-level data for 2030 and 2040. Thus, since 2050 is also a target year for FlexPlan activities, a complementary methodology was created to build the 2050 scenarios. This methodology consists of two main steps: 1) use trends demonstrated in TYNDP2020 using a linear approximation using 2030 and 2040 values to obtain 2050 data and 2) validate obtained results using another well-known and accepted data source. For this purpose, the European Commission long-term climate strategy, A Clean Planet for All, was selected [2].

As the EC package A Clean Planet for All provides its own scenarios, a comparative analysis was performed on a near one-to-one basis. The FlexPlan NT scenario was compared and adapted using as main source the ELEC scenario from A Clean Planet for All. ELEC is a scenario developed to reach 80% of emissions in 2050 (when compared to 1990) driven by electricity as the main energy carrier. DE and GA were directly compared to 1.5TECH and 1.5LIFE, which aim at achieving a 100% reduction in emissions. In fact, ENTSO-E already used these two scenarios as a basis for the creation of DE and GA scenarios, so they are completely in line with targets. Table 1 includes the final installed capacity at the EU level for the different technologies and the three considered scenarios.

Table 1. 2050 installed capacity by technology for the three FlexPlan scenarios.

Description	2050 Installed Generation Capacity [GW]		
	NT	DE	GA
Nuclear Power	66	69	62
Lignite	0	0	0
Hard Coal	0	0	0
Oil	1.9	1.9	1.9
Natural gas	182	91	91
Other fossil fuels	63	63	63
Mixed Fuels	0	0	0
Wind onshore	471	792	531
Wind offshore	186	111	221
Solar	611	1076	596
Biomass	1.4	1.5	1.4
Other RES	38	38	37
Run of river Hydro	56	56	56
Storage Hydro	77	77	77
Pumped storage Hydro	105	105	105
Battery	109	198	62
Demand Side Response (DSR)	34	49	49
Power-to-gas (P2G)	5	5	2
Total	2006.3	2733.4	1955.3

As can be seen in Table 1, to reach the climate targets, the lignite- and coal-installed capacity will reach zero or negligible values and fossil fuels will be based on natural gas and decarbonised fossil fuels. While NT and GA scenarios present a similar total installed capacity (around 2 TW), the DE scenario includes a 37% more installed capacity.

This is due to the fact that the DE scenario mostly bases the decarbonisation strategy in distributed energy resources such as solar technologies, resulting in the need to have additional installed capacity to ensure system security levels. Figure 9 depicts the evolution of the total installed capacity per technology for the DE scenario, considering the three targets years for FlexPlan studies. Again, one can see that the climate targets are reached in this scenario through ambitious increases in the total installed capacity for wind and solar technologies, while most fossil fuels will decrease to residual values. It is also worth mentioning that according to this scenario, batteries will also play an important role (directly linked to wind- and solar-installed capacities), with a total installed capacity rising from 23 GW in 2030 to 198 GW in 2050, representing a share of 7.2% of all installed capacity.

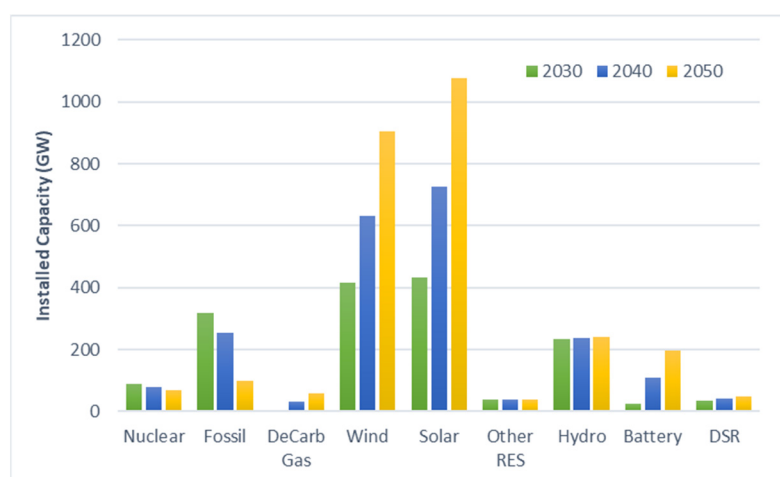


Figure 9. Distributed Energy (DE) scenario: evolution of installed capacities per technology, from 2030 to 2050.

The full methodology and a detailed analysis of each scenario are already available in [23]. The national-level values for these scenarios are then used as input for the regionalisation model explained in Section 4.2.

4.1.2. Grid Model

The scenarios' data are complemented by comprehensive and realistic regional case-level grid models. These grid models consider the existence of full geo-referenced transmission and distribution systems, existing and planned power plants and realistic load distribution. The transmission systems are based on a dataset received from ENTSO-E TYNDP 2018 (extra-high-voltage grid) [5], complemented with national-level and open source data (e.g., TSO network development plans and open street maps) for the sub-transmission levels. Distribution systems are built using synthetic networks, which are representative of real distribution networks around Europe.

The ENTSO-E model includes 25 sets of Common Grid Model Exchange Standard (CGMES) files, one for each continental Europe country whose TSOs belong to ENTSO-E and an additional file establishing the border conditions between the different countries. The model corresponds to a 2025 operational scenario with generation and load balances corresponding to market simulations performed by ENTSO-E in TYNDP 2018. The model contains network data for voltage levels between 110 kV and 750 kV. All elements connected to levels at 220 kV and above are modelled explicitly, while branches and substations below this threshold might not be represented in detail, depending on the country analysed. Load values are represented aggregated in the extra-high-voltage connection point, and embedded generation is connected to the near-EHV or high-voltage node. In the case of Nordic countries, the corresponding grid models are not included in the ENTSO-E dataset. Thus, a specific grid model was created. This model is based on the PyPSA-EUR dataset [24], complemented with national-level data obtained from the multiple Nordic TSOs.

The transmission systems model from ENTSO-E is missing sub-transmission levels in different countries, and this information is of utmost importance for FlexPlan studies as the final goal is to have a single grid model including transmission and distribution systems. Thus, to obtain sub-transmission grid models, additional data are required. These data were collected using open source data sources such as individual TSO network expansion plans and open-street-map-based solutions. When network data as electric parameters of grid elements are not available, average values are taken from the literature (e.g., typical impedance and capacity for overhead lines, considering the different voltage levels).

Distribution grid models are built using a methodology [25] to create synthetic networks, which are representative of the real distribution systems of the different countries involved in the regional cases. For this purpose, a statistical analysis was first performed on real grid models from multiple countries to obtain the statistical parameters required to create these synthetic networks. The adopted methodology, which has been tested for the Italian scenario [26], proved effective even when a limited amount of distribution network information was publicly available.

Each regional case grid model requires then the integration of these different datasets from multiple sources (ENTSO-E model, open source data and synthetic distribution network creation). As a first step of the regional case simulation, the grid models will also be validated, together with the data obtained for the first energy scenarios through the execution of a multi-temporal OPF algorithm (considering the 8760 h of the first target year for one scenario), ensuring that the grid models are representative and well modelled.

4.1.3. Complementary Data

To execute the regional case simulations, the energy scenarios and grid models need to be complemented with additional data sources, allowing for a full demonstration of the FlexPlan tool capabilities. These include detailed information related to generation units and major loads, which can be used for the demand side response. Generation data need to include at least the type of fuel, installed capacity, commissioning and decommissioning year for the power plant and its geographic location. These data are required for all generators connected to the system, which, by itself, represents a complex data collection process. As it is also the goal of FlexPlan to perform environmental impact assessment studies, a complementary set of data is also required to operationalise this activity. This environmental impact is separated into three complementary and quantifiable impacts, landscape, air quality and carbon footprint, each one with particular data needs.

Landscape impact analysis, based on an optimal routing algorithm for overhead lines [8], requires mostly the existence of geographic information regarding grid nodes and possible pathways for grid expansion candidates.

Air quality studies use a simplified air quality model to assess the impact of thermal generation. To execute this model, a comprehensive set of data is being collected for all thermal power plants at the national level. For each thermal power plant, implicit characteristics such as installed capacity, fuel type, stack geometry and pollutant emissions are considered as input data for the air quality model. Data are being collected for individual power plants, as it is the goal of FlexPlan to have results as close to reality as possible. When an individual power plant is not available, representative values are used (for fuel type and installed capacity).

Finally, carbon footprint analysis aims at calculating all the emissions of greenhouse gases occurring during the entire life cycle of the studied elements. Our approach includes the analysis of the carbon footprint of different grid expansion candidates. The considered grid components in this framework are new lines, new storage systems, new HVDC converters and phase shifter transformers. Since new generators are not considered as candidates for the FlexPlan tool, for the sake of simplicity, the carbon footprint evaluation will not consider power plant construction and decommissioning. This means that the carbon footprint of enabled energy production will be limited to the electricity produced by thermal power plants, as far as the carbon footprint of electricity production from

non-thermal renewable power plants (wind, solar, hydro) is mainly due to power plant construction and decommissioning. Keeping in mind the life cycle perspective of the carbon footprint concept, we will consider the emission due to energy source extraction (including biomass cultivating), fuel production and fuel combustion in the power plant. Identified data needs to perform this activity include fuel type, efficiency and installed capacity of thermal generators.

4.2. Pan-European Simulation

The pan-European scenarios described above provide data at a national level, but they do not include information about the exact location of RES and loads. However, this information is essential to analyse future power grids. Hence, a methodology for determining the spatial distribution is applied. For this, the electricity market and transmission grid simulation framework MILES [4] is used. The regionalisation module of MILES spatially distributes national scenario data in terms of installed RES capacities as well as demand and calculates time series for feed-in of RES and the electric load in a second step. As MILES is dedicated to detailed system studies with a strong focus on the German system, the regionalisation methodology is adapted to the different countries' individual geographic circumstances.

The regional distribution of RES is based on information about existing power plants as well as on regionalisation factors. Information about existing plants is firstly gathered from power plants matching [17] and expanded by the partners of the relevant European region on the basis of their know-how. Regionalisation factors ($F_{Regionalization}$), describing the percentage of the total installed capacity, which is installed in the considered region, (F_{Region}^n), are formed based on the land use, employing Corine Land Cover data [27].

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

One-dimensional factors ($n = 1$) consider one set of input data; for multi-dimensional factors ($n > 1$), the main parameter is weighted by an additional factor, e.g., the population density.

Locations for hydropower plants require very specific geographic conditions. Assuming that future plants will be built close to existing ones, the above-mentioned existing plants are scaled up to the required installed capacity. To avoid this resulting in very large power plants, the installed capacity is divided among the surrounding nodes. As wind power plants are mainly installed in agricultural areas with little population, the regionalisation factor for wind uses land data, weighted reciprocal to the population density. Figure 10 shows exemplary data for France. For photovoltaics (PV), distinction has to be made between countries with high solar irradiation and countries with less solar irradiation. In southern countries with higher solar irradiation PV systems are mainly ground mounted. A one dimensional regionalisation factor is used assuming that PV systems are primarily installed on non-irrigated arable land [27]. In countries with less solar irradiation, like Germany, the majority of PV systems are mounted on rooftops; hence in this case, it is assumed that they are located in urban areas. The load is distributed proportional to the population density.

Based on the spatial distributions, time series are generated using meteorological data. To calculate the generation for run-of-river (RoR) power plants, historical capacity factors from [28] are used. Reservoir power plants are assumed to cover the load, and thus their generation time series are created proportional to the load. For PV, the sun position is determined, and further, direct as well as diffuse irradiation is used to calculate the solar generation. The feed-in of wind power plants is calculated using the wind speed and an average characteristic wind curve. Load time series are created based on historic data.

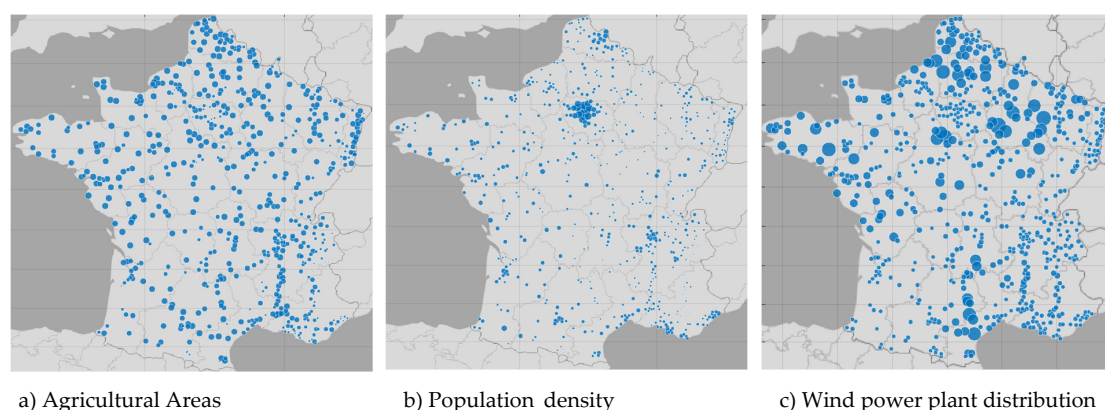


Figure 10. Methodology for spatial distribution of wind power plants in France.

4.3. Monte-Carlo-Based Time Series Generation and Market Simulation

As the FlexPlan approach aims at explicitly incorporating storage and demand flexibility in the planning process, the consideration of consecutive time steps, i.e., time series data, is essential. Hence, time series data for non-dispatchable units and loads represent a relevant input for the planning tool. Non-dispatchable units typically include variable renewable energy sources (vRES) in terms of wind and solar power. Furthermore, hydropower is partly non-dispatchable, especially RoR generation. Figure 11 exemplarily shows the historic variability in the normalised onshore wind power generation potential in selected European countries for 40 historic years. The variability is shown by a fan chart, presenting the all-time median as well as the percentiles highlighting several confidence intervals of the normalised power generation potential over time from 1980 until 2019 on an hourly basis. To improve visibility, weekly moving averages are plotted.

As can be seen from Figure 11, the national wind power generation potential during the years has been subject to strong volatility over the past 40 years throughout Europe. The diverse weather conditions, especially wind speed at hub height, at various turbine locations change over the course of time and thereby lead to steep gradients in wind power generation. The local time-dependent meteorological conditions are the main driver for the power generation potential. The meteorological conditions change not only during the year but also from year to year (cf. Figure 12), resulting in years with high and low wind potential, on average. Thus, the future power generation potential of vRES is subject to uncertainty. Wind power is only one exemplary vRES facing variability in its production due to external effects, e.g., weather conditions. Besides wind power generation, PV or more general solar power generation faces fluctuations in its power generation potential (cf. Figure 13) also, especially, due to the day–night fluctuations as well as the level of cloudiness. In addition, power generation of hydropower plants, especially RoR, is subject to yearly variability due to meteorological and hydrological conditions. Therefore, historical years can be classified as dry or wet weather years with comparable low or high hydropower generation potentials, respectively. Additionally, the electricity demand faces diurnal fluctuations and variability throughout the year due to external effects, namely day–night temperature fluctuations and seasons. Taking the above-mentioned variability of vRES, RoR and load into account, the amount of uncertainty in forecasting the future energy system becomes quite evident. Hence, it is essential to consider the variability of non-dispatchable units and loads in long-term power system planning adequately, as different combinations of high/low RES with high-/low-demand years might request very different grid expansion measures.

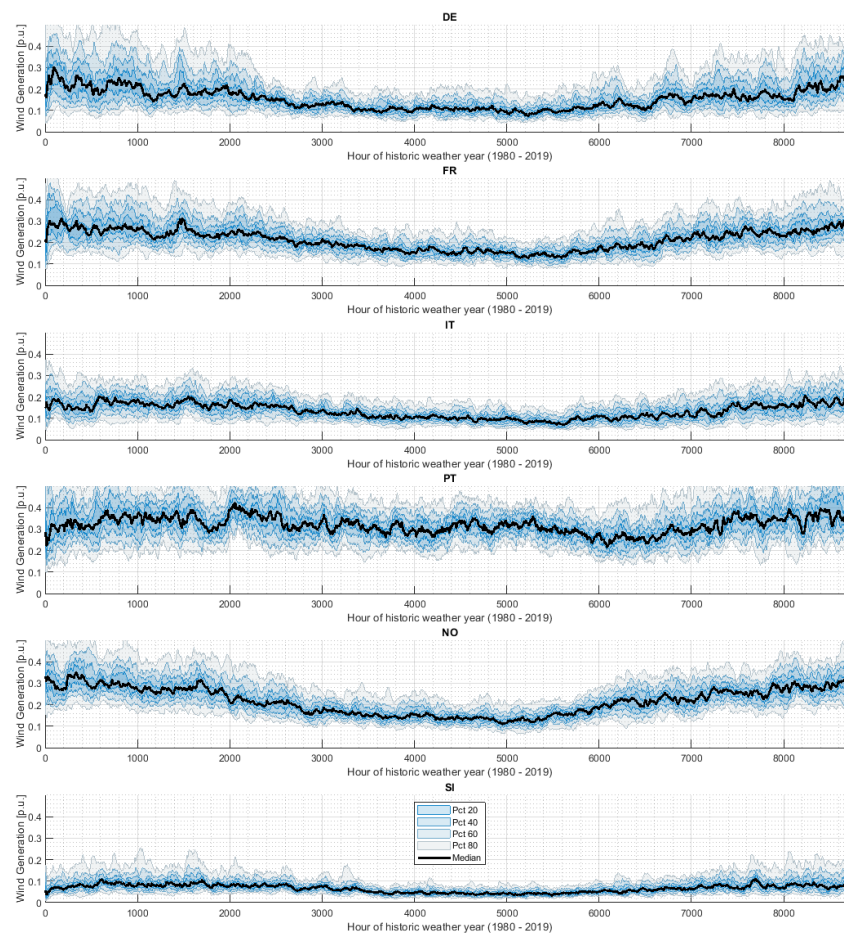


Figure 11. Normalised hourly wind power generation potential from 1980 to 2019 in selected European countries.

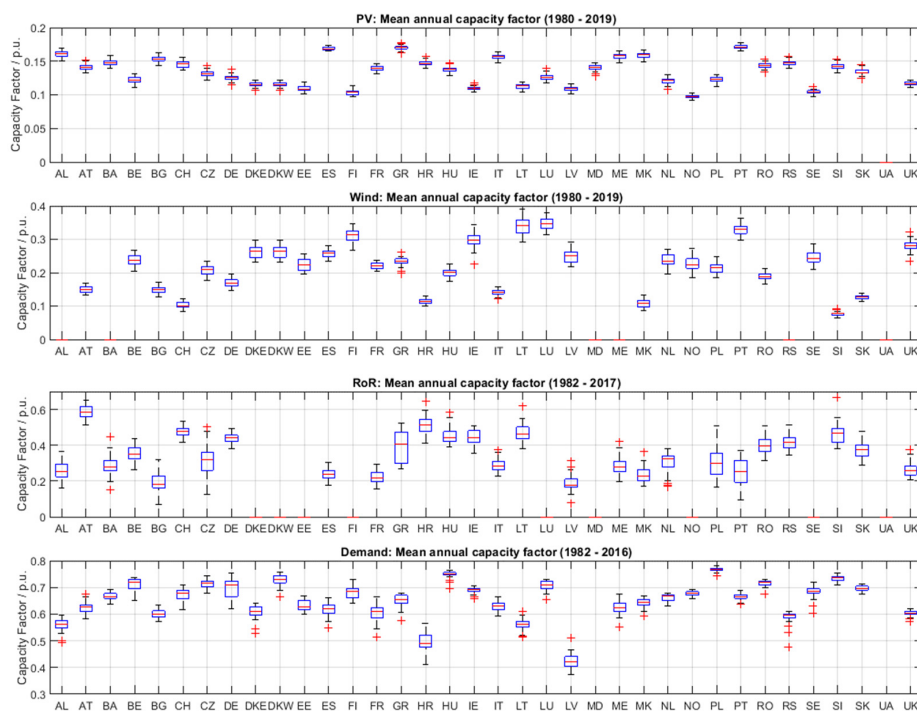


Figure 12. Variability in historical solar, wind onshore and hydro run-of-river as well as load capacity factors.

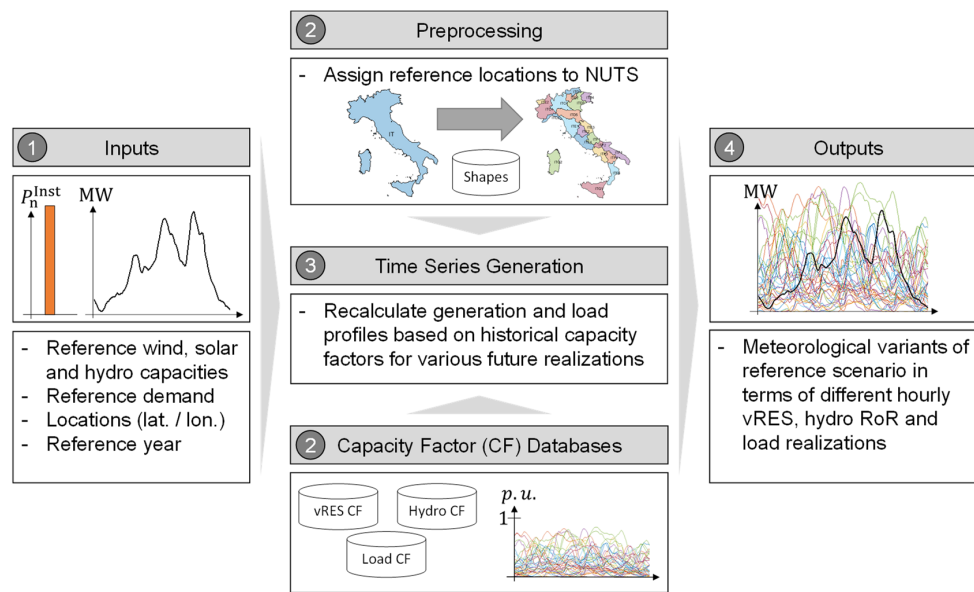


Figure 13. Schematic overview of the process generating meteorological variants for the Monte Carlo approach.

To consider future power generation of intermittent RES and their characteristic uncertainties, the FlexPlan approach makes use of stochastic modelling techniques, namely a Monte Carlo approach. The FlexPlan project focuses on long-term grid planning. As such, the Monte Carlo approach considers long-term uncertainties (climatic, meteorological and hydrological conditions) to create various meteorological variants as an input for the FlexPlan planning tool containing divergent combinations of generation and load realisations. The Monte Carlo approach does not consider short-term uncertainties, e.g., forecast errors or power plant outages.

Figure 13 schematically shows how meteorological scenario variants for FlexPlan's Monte Carlo approach are created based on the pan-EU macro-scenarios as a reference.

A reference scenario builds the foundation for the generation of meteorological scenario variants. A reference scenario includes forecasts of the installed capacities of wind, solar and hydropower as well as of the demand for a future scenario year. As the spatial distribution of capacities in each country is calculated with the presented MILES model, the reference capacities already include regionalisation on a sub-national level (e.g., per transmission grid node). Since the reference capacities' spatial distribution is more detailed than the Nomenclature of Territorial Units for Statistics (NUTS)-2-Level, an intermediary step is necessary to generate meteorological variants.

Second, the scenario generation approach assigns exactly one NUTS-2-Region to each location (defined by its latitude and longitude) of the reference scenario. To do so, the method uses a database containing the NUTS regions' shapes from [18]. This pre-processing step is mandatory, as the raw data used to create new meteorological variations are only available on NUTS-2-Level [13–15].

In a third step, the method creates various meteorological variants of the provided reference scenario. For this purpose, it uses the reference scenario's installed capacities as well as historical data in terms of capacity factors. A capacity factor $CF_{\Delta t}^{\text{Tech}}$ for an exemplary technology is defined in general as the ratio of realised generation $E_{\Delta t}^{\text{Gen}}$ to the installed capacity P^{Inst} in a specific period of time Δt :

$$CF_{\Delta t}^{\text{Tech}} = \frac{E_{\Delta t}^{\text{Gen}}}{P^{\text{Inst}} \cdot \Delta t}$$

Thus, hourly capacity factors define a normalised maximum generation potential (in the interval (0,1) per unit) over time, which can easily be used to calculate annual time series data. Hence, historical data were collected and pre-processed to create three capacity

factor databases. One database for each non-dispatchable generation technology subject to variability as well as the load was created respectively.

The vRES capacity factors from [13] have a high temporal (hourly) and spatial (NUTS-2-Level) resolution. Furthermore, the vRES capacity factors are available for a representatively long period (past 40 years). A second database includes hydro-RoR capacity factors for the past 36 years (1982–2017) per ENTSO-E market area. The raw data are publicly available [22]. The third database includes load capacity factors for the past 35 years (1982–2016) per ENTSO-E market area. The raw data are publicly available [29].

In Figure 13, the variability in mean annual capacity factors is depicted per country for the mentioned historic periods of time to give an impression of the data basis.

In a final step, the scenario generation approach creates meteorological variants $s \in S_s$ for the macro-scenario $m \in S_M$ by recalculating the technology-specific feed-in $P_{n,t,m,s}^{\text{Gen}}$ at each reference location $n \in S_N$ based on the technology-specific hourly capacity factor $CF_{r,t,s}^{\text{Tech}}$ of the NUTS-2-Region $r \in R$ and the reference location $n \in S_N$ is located in:

$$P_{n,t,m,s}^{\text{Gen}} = P_{n,m}^{\text{Inst}} \cdot CF_{r,t,s}^{\text{Tech}} \quad \forall n \in S_N, \quad \forall t \in S_T$$

For each macro-scenario $m \in S_M$, a maximum of 40 different meteorological realisations in terms of generation and load patterns are created as an input for the Monte Carlo approach. Each meteorological variant $s \in S_s$ (1980–2019) has a unique global load and generation pattern with respect to its temporal and spatial features, resulting in a broad variety of diverse combinations of vRES generation and load in Europe. To put concisely, individual climatic conditions are considered per NUTS-2-Region to model spatial correlations in wind and solar power generation all over Europe. Hence, the FlexPlan planning tool will take into account uncertainties in future power generation as well as demand by a Monte Carlo approach in terms of various weather conditions.

The resulting time series for RES and loads are input for an economic dispatch of the thermal power plants, which is calculated using the market simulation module of MILES [30]. Based on the overall generation and load per country, cross-border exchanges are identified. These boundary conditions make it possible to split the pan-European grid into coherent regional cases.

4.4. Grid Simulations in Regional Cases

The execution of each one of the six FlexPlan regional cases requires a set of complex operations which, in practice, corresponds to the aggregation of the different datasets, as described above.

This simulation, performed through the FlexPlan tool, requires two main datasets: the grid model and the scenario to be simulated. The grid model corresponds to the model obtained including the full topology of the transmission and distribution systems of the countries included in the regional case, using also real NTC and power flows among the different countries. Border conditions to countries external to the regional case are obtained through market simulations which are modelled using equivalent nodes. The above-mentioned complementary data for generation units and major loads are also required.

Complementing the grid model, the tool requires as input the energy scenario to be simulated. From the regionalisation process described above, time series for vRES and load are obtained at the zonal level. Thus, these data need to be converted into a grid nodal level. Generation data should be converted in a straightforward way as the regional cases have the full list of generators connected to the system. Additional installed capacity when compared to the current grid connections is solved following the methodology presented before (e.g., new hydro-installed capacities are treated as rating up of existing power plants). For the adaptation of the load time series, a more complex methodology is required, as it implicitly requires the distribution of zonal load values to different grid nodes, mostly at the distribution side, which should be representative of the real distribution system for that particular area. This methodology, still under development, will use existing public access data from distribution system operators to achieve a representative distribution

(e.g., taking into consideration the natural load levels of the different distribution primary substations). When these data are not available, regional cases will use their knowledge of the different countries distribution networks, together with the already filtered results from the regionalisation process, to achieve a fair share of load distribution.

Each one of the nine energy scenarios will be simulated considering hourly time series for the target year in analysis, corresponding to 8760 snapshots simulated. An OPF is performed to the full time series of each target year to identify Lagrange multipliers required for the creation of grid expansion candidates, and these are then presented to the regional case developers. Thus, the execution of the regional cases corresponds to a validation of all previously described datasets and methodologies.

5. Preliminary Results on a Small-Scale Test System

A software package named FlexPlan.jl has been created in Julia/JuMP language [31] as a proof-of-concept implementation of the planning model described in Section 2. The implementation makes use of the PowerModels.jl [32] and PowerModelsACDC.jl [11] packages and make it possible to test specific parts of the planning model independently. This allows users to test specific parts of the planning model in greater detail without having to solve the full planning model at all time. Further, the implementation allows to assess the computational performance of the planning model for a variety of open source and commercial optimisation solvers. In the course of the project, FlexPlan.jl will serve as the test bed for the full planning tool, as envisaged within FlexPlan, to carry out tests with respect to flexibility, storage and reliability modelling; model decomposition techniques; quality of scenario reduction techniques; and environmental modelling. The following paragraphs provide preliminary test results achieved with FlexPlan.jl.

The test system, as shown in Figure 14, is used to validate the planning model. As network data, the six-bus Graver system is used [33]. The test network has been projected on Italy for further validation of the environmental modelling of the FlexPlan model. Conventional generation is assumed to be located in the North and South Central nodes. Wind and PV generation is located on the South Central and Sicily nodes, which is assumed not to be connected to rest of the system (as a characteristic of the six-bus Garver system [33]).



Figure 14. Italian test system used for proof-of-concept validation.

There are four storage candidates on the North, Central North, Sardinia and Sicily nodes, three candidate HVDC connections between Sicily and the mainland and three candidate AC connections. In addition, demand flexibility candidates according to the model presented in Section 2 are defined for each demand node. The test case is constructed such that investments are required to connect the renewable energy sources on Sicily to

the main system. In addition, investments either in storage or in demand flexibility are required in order to avoid expensive demand curtailment.

Using the Monte Carlo scenario generation and reduction approach, 35 yearly time series have been created based on the historical data for renewable generation and demand in Italy. For the illustrative results shown in the following paragraphs, these time series have been reduced to six monthly time series clusters (time series length of 720 h) using both PCA and k -means clustering, as described in Section 2. For the results shown, two cases have been used. In the flex case, the demand flexibility is modelled as described in Section 1, and in the non-flex case, only involuntary demand curtailment has been allowed. All calculations have been performed on a personal computer with a Quad-Core Intel i7 processor (2.8 GHz) with 16 GB of RAM. The calculation time for the analysed test cases has varied between 56 and 598 s.

Figure 15 shows the total costs obtained for both cases. Firstly, we can observe that depending on the chosen Monte Carlo time series, there can be a large variance in the total system costs. This variation stems mainly from the differences in renewable energy generation and the demand, affecting the operational costs of the system. Secondly, we can also observe that in the presence of flexible demand, the total system costs are approximately 10% lower, as less grid storage is required.

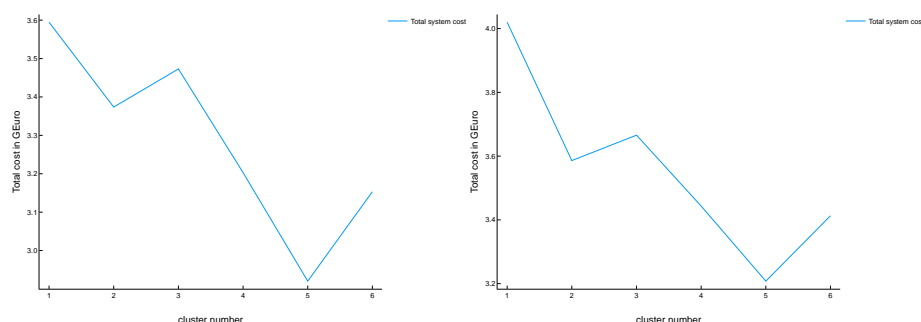


Figure 15. Total system cost for flex (left) and non-flex (right) cases.

The investments into HVDC connections for both cases are the same, as depicted in Figure 16. In both cases, an HVDC submarine connection from Sicily Italy South is built. Nevertheless, in the non-flex case, the storage candidate on Sardinia is chosen by the optimiser, as otherwise the demand cannot be satisfied without significant load shedding costs.

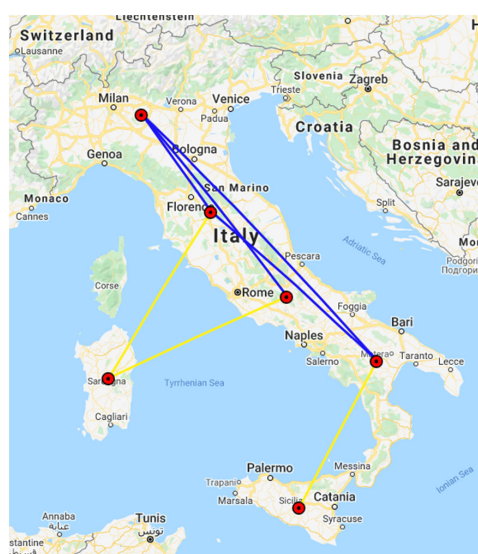


Figure 16. Optimal transmission grid layout for flex and non-flex cases.

6. The Regulatory Framework

The recent package Clean Energy for All Europeans by the European Commission [34] has confirmed the pan-European political determination to integrate energy flexibility services as a consistent part of both operation and planning of the electricity network. One of the key documents in the package, the Internal Electricity Market (IEM) Directive (2019/944) [35], specifies already in the opening lines (61) that distribution system operators (DSOs) should be incentivised to use distributed resources in order to avoid costly network expansions.

6.1. Incentives for Use of Flexibility

The directive clearly requires (art. 32) that DSOs' future distribution network development plans consider demand response, energy efficiency, energy storage facilities or other resources as an alternative to system expansion. Coming to TSOs, the same document (art. 51) prescribes that they fully take into account the potential for the use of demand response, energy storage facilities or other resources as alternatives to system expansion, when elaborating ENTSO-E TYNDP. The Internal Energy Market (IEM) Regulation (2019/943) from the same package [36] requires in provision (3) that to foster the integration of a 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.

It is natural to expect that to successfully meet the above-mentioned requirements, a legal and regulatory environment must be created for empowering the use of flexibility for network planning and operation with cost-efficient results. Uncertainty and especially the absence of clear regulatory provisions are possibly two of the most significant barriers to establishing new services, since this uncertainty could strongly discourage potential investors from developing the necessary infrastructure assets. Furthermore, to establish an operational environment, it can be equally important to indicate roles and responsibilities as well as any possible limitations of these in order to draw unambiguous legal borders.

6.2. Ownership and Operation of Energy Storage

The most recent recast of the IEM directive reaffirms in art. 36 and 54 the position stated before, not allowing system operators (SOs) to own, develop, manage or operate energy storage facilities. However, the European Commission (EC) shows a very pragmatic approach on several critical issues as, for example, the ownership and operation of energy storage. The most recent version of recasts has been partially modified, taking into account input coming from some stakeholders, expending the possible terms of derogation for SOs for operational purposes, where they are fully integrated network components and the regulatory authority has granted its approval, or where all of the following conditions are fulfilled [36] (almost similar conditions for DSOs and TSOs in, respectively, art. 36 and 54):

- (a) Other parties, following an open, transparent and non-discriminatory tendering procedure which is subject to review and approval by the regulatory authority, have not been awarded a right to own, develop, manage or operate such facilities or could not deliver those services at a reasonable cost and in a timely manner.
- (b) Such facilities (or non-frequency ancillary services for TSOs) are necessary for the SOs to fulfil their obligations under the directive for the efficient, reliable and secure operation of the system, and they are not used to buy or sell electricity in the electricity markets.
- (c) The regulatory authority has assessed the necessity of such a derogation, has carried out an ex ante review of the applicability of a tendering procedure, including the conditions of the tendering procedure, and has granted its approval.

6.3. Ownership and Operation of Electric Vehicle (EV) Charging Stations

According to the opening provision (61) in the IEM directive [35], DSOs should be enabled, and provided with incentives from the member states, to use services from distributed energy resources such as demand response and energy storage. According to

art. 33 in the same document, DSOs shall not own, develop, manage or operate recharging points for electric vehicles (EVs), except solely for their own use. DSOs can be allowed to own, develop, manage or operate recharging points for EVs, provided that all of the following conditions are fulfilled:

- (a) Other parties, following an open, transparent and non-discriminatory tendering procedure which is subject to review and approval by the regulatory authority, have not been awarded a right to own, develop, manage or operate recharging points for electric vehicles or could not deliver those services at a reasonable cost and in a timely manner.
- (b) The regulatory authority has carried out an ex ante review of the conditions of the tendering procedure under point (a) and has granted its approval.
- (c) The DSO operates the recharging points on the basis of third-party access and does not discriminate between system users or classes of system users, and in particular in favour of its related undertakings.

6.4. New Provisions for Demand Response

According to art. 31, describing tasks for DSOs, they are required to ensure the effective involvement of all qualified market participants, including market participants offering energy from renewable sources, market participants engaged in demand response and operators of energy storage facilities in procurement of the products and services necessary for the system operation. This shall be ensured by the regulatory framework in the member states.

Following art. 33, several European countries elaborate very ambitious plans for electrification of transport, making development of the new EV charging stations to become one of the main reasons for the expansion of distribution networks in the coming years. The directive [35] points out in provision (41) that demand response is pivotal for enabling smart EV charging. In addition, provision (42) refers to EVs as a potential storage for demand response application. Combination of these factors means, in practice, that the expansion plans for distribution networks should meet the growing demand for electric transport but should also consider its demand response potential as a consistent part of the planning approach.

7. Conclusions

By taking into account the recent regulation provisions highlighted above, it appears evident that there are presently clear and strong regulatory signals prompting European SOs to consider flexible resources as a new important active subject in the grid expansion planning process. In addition to this, the commission outlines opportunities for doing so by formalising several working instruments, in particular the energy storage and aggregated demand response. What is still lacking and urgently missing is a sound planning methodology able to employ and implement all such legislative instruments so as to achieve the goal of a full valorisation of system flexibility in the grid-planning procedures. This strengthens once again the importance and proper timing of the FlexPlan project, both for testing new innovative grid-planning methodologies and for coping with the present challenges.

It is also clear that despite the recent significant steps ahead, the present regulatory framework is still under development and will become mature during the coming years. One of the main planned outcomes of the FlexPlan project are the regulatory guidelines, which will try to clarify opportunities and regulatory barriers in the use of flexibility by SOs, trying to suggest which regulatory provisions could support exploiting flexibility potentials in an optimal way, based on the developed FlexPlan methodology and simulation results.

Investments in storage and flexibility will remain mostly in the hands of private investors. Consequently, national regulatory authorities (NRAs) should translate the suitability of deploying new storage or flexibility in strategic network locations into opportune incentivisation schemes. This is an important new element with respect to traditional grid planning, which was limited to formulate investment needs in new power lines which

could be carried out by the same entities (SOs) which had performed the study. Now, NRAs should be able to translate the opportunity for new investments in system flexibility into targeted incentivisation provisions so as to stimulate private investments in the sites where SOs indicate the opportunity. This could make everything more complicated.

In an alternative regulatory vision, NRAs could charge SOs to set up calls for bids for investing in promising locations. In this case, it would be the SOs themselves which, according to the results of their studies, would act on investors in order to drive optimal investments.

A final possibility is that strategic locations are managed with storage devices directly installed by the SOs, provided that, given their natural monopoly position, they are managed in a non-profit-oriented way, similarly to must-run power plants (art. 54-1(b) of the IEM [35]).

Once flexibility investments are carried out, flexibility should be negotiated in real-time markets dealing with grid congestion. Therefore:

- Such markets should be able to reflect real locations for congestion so as to provide optimal price signals (nodal markets would be essential for that) able to orient aggregators' bidding.
- Market products should be defined so as not to create entry barriers and not to discriminate any potential flexibility provider.

In the light of this, the regulatory guidelines which will be elaborated in the conclusive phase of the FlexPlan project will be able to help, on the one side, SOs to update their planning procedures and, on the other, NRAs to elaborate the right future regulation by taking into account prospects on the real role flexibility can play in the future, as coming out of the detailed FlexPlan scenario analysis for 2030, 2040 and 2050.

Author Contributions: G.M., project coordinator of FlexPlan, defined the overall structure of the paper and wrote the abstract, introduction and conclusions, as well as small parts of Sections 2 and 3. H.E. wrote Section 2 (mathematical modelling) and Section 5 (small-scale tests), R.R.-S. wrote Section 3 (pre-processor), and N.A. coordinated writing Section 4 (scenarios) to which A.E., J.G. and B.M. contributed, too. A.M. wrote Section 6 (regulatory framework). D.S. and M.R. contributed to Section 2. M.M., M.H. and G.L. provided a final contribution to homogenise the paper. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results/this publication received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 863819.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are not publicly available due to the fact that part of them has been drawn from non-public data that are part of the know-how of the involved project partners.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. European Parliament. Energy: New Target of 32% from Renewables by 2030 Agreed by MEPs and Ministers. 2018. Available online: <https://www.europarl.europa.eu/news/en/press-room/20180614IPR05810/energy-new-target-of-32-from-renewables-by-2030-agreed-by-meps-and-ministers> (accessed on 12 January 2021).
2. European Commission. *A Clean Planet for All—A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*; European Commission: Brussels, Belgium, 2018.
3. EUPHEMIA Public Description. Available online: <https://www.europex.org/wp-content/uploads/2016/11/Euphemia-Public-Description.pdf> (accessed on 12 January 2021).
4. Teuwsen, J.; Liebenau, V.; Rehtanz, C. Comparison of regionalization methods for network development planning. In Proceedings of the IEEE PES ISGT Europe 2013, Lyngby, Denmark, 6–9 October 2013; pp. 1–5. [CrossRef]
5. ENTSO-E. ENTSO-E Grid Model for TYNDP 2018. 2018. Available online: <https://www.entsoe.eu/publications/statistics-and-data/#entso-e-on-line-application-portal-for-network-datasets> (accessed on 13 January 2021).
6. European Commission and Joint Research Centre. *Distribution Network Models Platform Guidelines*, 2nd ed.; European Commission: Brussels, Belgium, 2019.

7. ENTSO-E and ENTSO-G. *TYNDP2020—Scenario Report*; ENTSO-E: Brussels, Belgium, 2020.
8. Ergun, H.; Rawn, B.; Belmans, R.; van Hertem, D. Optimization of transmission technology and routes for Pan-European electricity Highways considering spatial aspects. In *Proceedings of the 2015 IEEE Eindhoven PowerTech*, Eindhoven, The Netherlands, 29 June–2 July 2015; pp. 1–6. [\[CrossRef\]](#)
9. Hart, P.; Nilsson, N.; Raphael, B. A Formal Basis for the Heuristic Determination of Minimum Cost Paths. *IEEE Trans. Syst. Sci. Cyber.* **1968**, *4*, 100–107. [\[CrossRef\]](#)
10. Dave, J.; Ergun, H.; An, T.; Lu, J.; van Hertem, D. TNEP of meshed HVDC grids: ‘AC’, ‘DC’ and convex formulations. *IET Gener. Transm. Distrib.* **2019**, *13*, 5523–5532. [\[CrossRef\]](#)
11. Ergun, H.; Dave, J.; van Hertem, D.; Geth, F. Optimal Power Flow for AC–DC Grids: Formulation, Convex Relaxation, Linear Approximation, and Implementation. *IEEE Trans. Power Syst.* **2019**, *34*, 2980–2990. [\[CrossRef\]](#)
12. Farivar, M.; Low, S.H. Branch Flow Model: Relaxations and Convexification—Part I. *IEEE Trans. Power Syst.* **2013**, *28*, 2554–2564. [\[CrossRef\]](#)
13. Pfenninger, S.; Staffell, I. Renewables Ninja. Available online: <https://www.renewables.ninja/> (accessed on 15 January 2021).
14. Staffell, I.; Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **2016**, *114*, 1224–1239. [\[CrossRef\]](#)
15. Pfenninger, S.; Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **2016**, *114*, 1251–1265. [\[CrossRef\]](#)
16. ENTSO-E. Transparency Platform. Available online: <https://transparency.entsoe.eu/> (accessed on 15 January 2021).
17. Gotzens, F.; Heinrichs, H.; Hörsch, J.; Hofmann, F. Performing energy modelling exercises in a transparent way—The issue of data quality in power plant databases. *Energy Strategy Rev.* **2019**, *23*, 1–12. [\[CrossRef\]](#)
18. EUROSTAT. Geographics for the Administrative Boundaries. Available online: <https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts> (accessed on 25 January 2021).
19. Steinley, D.; Brusco, M.J. Initializing K-means Batch Clustering: A Critical Evaluation of Several Techniques. *J. Classif.* **2007**, *24*, 99–121. [\[CrossRef\]](#)
20. Jolliffe, I.T.; Cadima, J. Principal component analysis: A review and recent developments. *Phil. Trans. R. Soc. A* **2016**, *374*, 20150202. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Micheli, G.; Vespucci, M.T.; Stabile, M.; Puglisi, C.; Ramos, A. A two-stage stochastic MILP model for generation and transmission expansion planning with high shares of renewables. *Energy Syst.* **2020**. [\[CrossRef\]](#)
22. ENTSO-E. *Mid-Term Adequacy Forecast 2018*; ENTSO-E: Brussels, Belgium, 2018.
23. Project FlexPlan. In *Pan-European Scenario Data*; 2020. Available online: <https://flexplan-project.eu/publications/> (accessed on 25 January 2021).
24. Hörsch, J.; Hofmann, F.; Schlachtberger, D.; Brown, T. PyPSA-Eur: An open optimisation model of the European transmission system. *Energy Strategy Rev.* **2018**, *22*, 207–215. [\[CrossRef\]](#)
25. Viganò, G.; Rossi, M.; Moneta, D. Generation of artificial distribution networks for the evaluation of advanced control solutions. In *Proceedings of the 2017 AEIT International Annual Conference*, Cagliari, Italy, 20–22 September 2017; pp. 1–6. [\[CrossRef\]](#)
26. Viganò, G.; Rossi, M.; Michelangeli, C.; Moneta, D. Creation of the Italian Distribution System Scenario by Using Synthetic Artificial Networks. In *Proceedings of the 2020 AEIT International Annual Conference (AEIT)*, Catania, Italy, 23–25 September 2020; pp. 1–6. [\[CrossRef\]](#)
27. European Environment Agency (EEA). *Copernicus Land Monitoring Service 2018*; European Environment Agency (EEA): Copenhagen, Denmark, 2018.
28. De Felice, M. *ENTSO-E Hydropower modelling data (PECD) in CSV format*, 4th ed.; ENTSO-E: Brussels, Belgium, 2020. [\[CrossRef\]](#)
29. ENTSO-E and ENTSO-G. *TYNDP 2020—Scenarios Data*; ENTSO-E: Brussels, Belgium, 2020.
30. Spieker, C.; Teuwsen, J.; Liebenau, V.; Muller, S.C.; Rehtanz, C. European electricity market simulation for future scenarios with high renewable energy production. In *Proceedings of the 2015 IEEE Eindhoven PowerTech*, Eindhoven, The Netherlands, 29 June–2 July 2015; pp. 1–6. [\[CrossRef\]](#)
31. JuliaLang. Julia Programming Language. Available online: <https://julialang.org/> (accessed on 16 January 2021).
32. Coffrin, C.; Bent, R.; Sundar, K.; Ng, Y.; Lubin, M. PowerModels. JL: An Open-Source Framework for Exploring Power Flow Formulations. In *Proceedings of the 2018 Power Systems Computation Conference (PSCC)*, Dublin, Ireland, 11–15 June 2018; pp. 1–8. [\[CrossRef\]](#)
33. Garver, L. Transmission Network Estimation Using Linear Programming. *IEEE Trans. Power Appar. Syst.* **1970**, *7*, 1688–1697. [\[CrossRef\]](#)
34. European Commission. Clean Energy for All Europeans Package. 2019. Available online: https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en (accessed on 24 January 2021).
35. 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*; European Commission: Brussels, Belgium, 2019.
36. European Commission. *Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the Internal Market for Electricity*; European Commission: Brussels, Belgium, 2019.

**C1 - POWER SYSTEM DEVELOPMENT & ECONOMICS
PS 3 / PLANNING UNDER UNCERTAINTY AND WITH CHANGING
EXTERNAL CONSTRAINTS**

The innovative FlexPlan methodology to reap the benefits of including storage and load flexibility in grid planning: methodology and regional study cases

Gianluigi MIGLIAVACCA (*)

RSE

Italy

Gianluigi.Migliavacca@rse-web.it

Stefania BALLAURO

RSE

Italy

Hakan ERGUN

KULeuven

Belgium

Maxime HANOT

N-SIDE

Belgium

Jawana GABRIELSKI

TU Dortmund

Germany

Nuno AMARO

R&D NESTER

Portugal

Andrei MORCH

SINTEF Energi

Norway

Raúl RODRÍGUEZ-SÁNCHEZ

TECNALIA

Spain

SUMMARY

In the last years, we are assisting to a high-speed deployment of Renewable Energy Sources (RES) in electric Transmission and Distribution (T&D) grids as well as to an increased penetration of Distributed Energy Sources (DER) in distribution grids. This is making grid planning activities more and more complex and affected by a high level of uncertainty and calls for a deep revision of the consolidated grid planning methodologies applied by the System Operators.

On this pathway, the FlexPlan project (<https://flexplan-project.eu/>) aims at establishing a new T&D grid planning methodology considering the opportunity to install new storage devices as well as to perform a flexible exercise of some loads located in selected grid nodes as an alternative to building new lines. Local compensation of RES generation spikes could allow to reduce the amount of congestion the grid is exposed to with a less expensive and less environment-impacting intervention.

This paper first analyses which aspects of the present consolidated grid planning methodologies applied by System Operators are becoming critical and then describes the key aspects of the new FlexPlan grid planning methodology aimed to overcome those criticalities. Then, the paper provides details on the reference scenarios adopted by FlexPlan for the three grid years (2030, 2040 and 2050) and provides the first results for the simulations carried out by each of the 6 regional cases. Finally, the paper provides some conclusions that can be drawn from these studies on the role flexibility will play in Europe in the medium-long term and on the benefits that can be reaped by taking it into account in the transmission and distribution grid planning process.

KEYWORDS - Grid Planning, Grid flexibility, Storage, Demand Side Management

INTRODUCTION

In the last years, we are assisting to a high-speed deployment of Renewable Energy Sources (RES) in electric Transmission and Distribution (T&D) grids as well as to an increased penetration of Distributed Energy Sources (DER) in distribution grids. This is making grid planning activities more and more complex and affected by a high level of uncertainty.

Grid investments are capital intensive and infrastructures lifetime spans over several decades. Due to widespread RES and DER deployment, the generation and load scenarios upon which the cost-benefit analyses for new grid infrastructures are based are continuously and rapidly changing. As a consequence, when a new line is commissioned, the techno-economic benefits it was initially supposed to provide could prove significantly lower than expected.

Additionally, building new lines meets more and more hostility from the public opinion, which makes planning activities even longer and affected by uncertainties.

Variable flows from RES are generating a new type of intermittent congestion which can sometimes be better compensated by resorting to system flexibility: in many cases, an investment in a new line/cable would not be economically justified.

On this pathway, the FlexPlan project (<https://flexplan-project.eu/>) aims at establishing a new T&D grid planning methodology considering the opportunity to install new storage devices as well as to perform a flexible exercise of some loads located in selected grid nodes as an alternative to building new lines. Local compensation of RES generation spikes could allow to reduce the amount of congestion the grid is exposed to with a less expensive and less environment-impacting intervention. This complies with the general terms and intentions of the European Directive on Internal Energy Market (2019/944) [1] and the corresponding Regulation (2019/943) [2], which were a part of "Clean Energy for all Europeans" package [3].

FlexPlan aims at providing the following contributions:

- Development of a new methodology and of a new tool optimizing T&D planning by considering the placement of new storage devices as well as the flexible exercise of some loads in selected grid nodes as an alternative to traditional grid planning. This methodology presents several very innovative aspects, among which: assessment of best planning strategy by analysing in one shot a high number of candidate expansion options provided by a pre-processor tool; simultaneous mid- and long-term planning assessment over three time frames (2030-2040-2050); incorporation of full range of Cost Benefit Analysis criteria into the target function; integrated transmission and distribution planning; embedded environmental analysis (air quality, carbon footprint, landscape constraints); probabilistic contingency methodologies in replacement of the traditional N-1 criterion; application of numerical decomposition techniques to reduce calculation efforts; analysis of variability of yearly RES and load time series through a Monte Carlo process.
- Application of this methodology to perform a grid planning analysis over six European regional cases by considering both the mid- and the long-term (2030, 2040, 2050) in one only optimization process. In addition, pan-European scenarios are run as well, in order to establish consistent border conditions for all 6 regional cases.
- Elaboration of regulatory guidelines aimed at providing National Regulatory Authorities with indications on the opportune regulation to be adopted for maximizing the benefits that can be obtained with the new grid planning methodology. These guidelines will be built by considering the potential role of flexibility and storage as a support of T&D planning, resulting from the outcome of the six regional cases analyses.

This paper first analyzes which aspects of the present consolidated grid planning methodologies applied by System Operators are becoming critical and then describes the key aspects of the new FlexPlan grid planning methodology aimed to overcome those criticalities. Then, the paper provides details on the reference scenarios adopted by FlexPlan for the three grid years (2030, 2040 and 2050) and provides the first results for the simulations carried out by each of the 6 regional cases. Finally, the paper provides some conclusions that can be drawn from these studies on the benefits that can be reaped by taking flexibility into account in the transmission and distribution grid planning process.

CRITICAL ASPECTS OF CURRENT PLANNING METHODOLOGIES

The new context described above should bring grid planners to rethink some foundations of the grid planning methodologies which are applied nowadays.

First of all, distribution networks are now subject to important changes, due to the installation of local generation and storage. Due to that, even the direction of power flows, traditionally from primary substations to the loads, are more and more frequently reversed: distribution networks are becoming able to deliver power to transmission networks. Along with power, distribution networks become able to provide services towards transmission (mainly: balancing and congestion management). Such services are extremely important to provide extra grid flexibility, so as to help integrating an ever increasing amount of Renewable Energy Sources (RES). In this context, distribution grids should abandon the traditional fit-and-forget grid planning methodology based on sizing the grid for a “worst case”. At the same time, transmission and distribution planning should become more and more integrated, in order to realise the best synergies between the two networks and minimize costs. However, taking into account that distribution and transmission planning are carried out by two distinct entities (Transmission System Operators - TSOs - and Distribution System operators - DSOs), it is also important that a certain decision autonomy is maintained between TSOs and DSOs as well as a separation on data management. FlexPlan proposes for the first time a methodology to manage this.

Another important rigidity of present grid planning procedures consists of the fact they don't co-evaluate a set of reinforcement candidates, so as to determine an economic optimum by considering both operative dispatch costs (OPEX) and capital costs (CAPEX), but they analyse one candidate a time by applying a with-and-without methodology which compares the total costs when the new candidate is present in the grid with the status quo before the investment is carried out (two versions are possible depending if all the other candidates are considered already installed or not, giving raise to the TOOT and PINT methodologies described in ENTSO-E Cost-Benefit Analysis [4]). As each investment influences the economical evaluation of the others, this methodology may bring to sub-optimal decisions.

Another aspect that is completely disregarded by present planning methodologies is that flexibility provided by storage elements and flexible loads can bring congestion management support, especially in the case of short duration congestion caused by RES variability patterns, for which investments in grid reinforcements would not be justified. So, the installation of storage elements in selected nodes as well as a flexible exercise of big loads could prove more efficient than grid reinforcements.

Present grid planning methodologies disregard, or consider in a very qualitative way, environmental externalities (effects on air quality, CO₂ lifecycle or landscape impact), whereas these aspects are more and more important because of growing public sensibility to environmental issues. In order to consider environmental costs in an objective way, it is important to implement a quantitative appraisal methodology allowing to internalize them, so as to put them on the same scale as all other costs.

Nowadays, grid procedures first carry out an optimization of the social welfare and then use the obtained results in a separated cost-benefit analysis. That can be a source of distortions and suboptimalities. A better approach would be implementing a cost-benefit methodology as fully integrated into the target function of the grid planning optimization procedure.

Another important aspect is that grid planning should now look forward till the long term (e.g. 2050 or even beyond) in order to gather a complete overview on the decarbonization path of the European system. So, long-term planning models should be elaborated. Such models should not solve one year a time (e.g. first 2030, then 2040, then 2050) because this approach brings to overestimate the needs for a given target year, conditioning the global optimum and potentially bringing to sub-optimal solutions. The optimisation should be carried out simultaneously for all target years. This enormously complicates the numerical problem, bringing to the necessity to apply decoupling procedures (e.g. Benders' decomposition) and/or relaxation methodologies.

Finally, contingency analyses based on the traditional N-1 methodology proves more and more fragile and not fit for an objective contingency appraisal (the same fault probability is considered for all branches). Many TSOs already begin to consider replacing N-1 with probability-based methodologies. However, such methodologies are extremely heavy from the computational point of view and their rigorous application to large computational cases (long-term planning, nodal approach for big counties

and hourly time resolution) often results computationally too heavy. Thus, it is important to search for simplified yet efficient methodologies.

As described in the following sections, all the above issues are considered altogether in the innovative approach carried out by the FlexPlan project.

OUTLINE OF FLEXPLAN INNOVATIVE PLANNING APPROACH

The main goal of the FlexPlan approach is to incorporate classical and flexible grid expansion options including their environmental impact in a network expansion optimisation model, capable of determining the optimal network investments under a multitude of future scenarios and operational conditions. The developed model is generic and can be applied to both transmission and distribution networks.

Figure 1 shows the structure of the optimisation model and the input parameters. A set of discrete 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 tool. These expansion candidates are characterised both technically and economically by the FlexPlan pre-processor. The installed conventional power generation capacity, RES generation and demand time series as well as transmission and distribution system data are used as input.

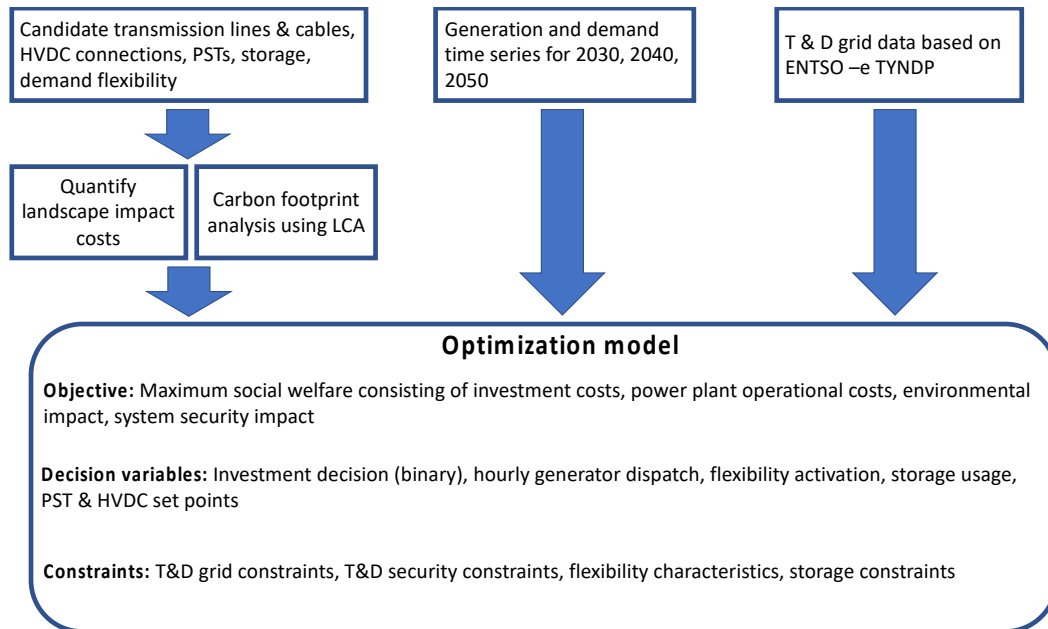


Figure 1 Building blocks, input and output parameters of the planning model

The objective of the optimisation model is to maximise social welfare. This is obtained by minimising the sum of T&D grid investment costs, operational costs bound to generation dispatch and environmental impact costs, while maximising the benefits achieved using the demand flexibility and storage. The resulting optimisation problem has been formulated as a multi-period, stochastic mixed-integer linear problem[5]. Discrete decision variables represent investment decision for AC and DC grid investments, demand flexibility and storage investments. An hourly resolution of the problem is considered over three investment years of the planning horizon, namely 2030, 2040 and 2050. The hourly resolution ensures the accurate modelling of demand flexibility actions, such as demand shifting and charging and discharging of battery energy storage systems. The model is formulated stochastically to account for different future developments with respect to RES penetration as well as climatic conditions. Including different probabilities for each scenario and representing the objective function as a probability weighted sum, a trade-off between all considered scenarios is found. The detailed objective of the optimisation problem is provided under [6].

To limit the computational burden of the optimization problem, a list of network locations and technology candidates for network extension is provided by a SW module. The reduction of investment decision options cuts down the number of binary variables in the formulation.

Flexibility resources, such as storage and loads representing demand response options, are presented as network candidates competing with conventional network assets. Two ways are provided to propose candidates to the planning tool: forced by the user and automatically calculated by the candidate pre-processor module. In the first case, the user, based on its knowledge about the network, can propose network extension candidates. This is specially recommended in two cases:

- Extension of the network between nodes that are not connected through lines in the non-expanded scenario.
- For technologies that require a dedicated study for their installation, e.g., HVDC, phase shifting transformers (PST) and pumped-hydro.

In the second case, the automated proposal of storage, flexible loads and conventional asset candidates is performed in four main steps:

1. Identification network congestions: the results of the non-expanded network Optimal Power Flow (OPF) carried out by the planning tool suite are the inputs that the pre-processor needs to perform this task. Lagrange Multipliers (LM), Locational Marginal Prices (LMP) and Power Transfer Distribution Factors (PTDF) are used, among others. Using this information congestions are identified and ranked based on their severity and occurrence. Considering this ranking, a number of locations is selected for network expansion.
2. Analysis of network congestions: once identified, the selected congestions are analysed more in detail through the identification of power flow directions, number of congestion hours, consecutive congestion hours, etc.
3. Check of locational constraints and characteristics: as part of the grid model definition, the user can provide additional characteristics related to each network node: type of bus (substation and types of load supplied, industrial load, generator), availability of resources, location of bus (rural or urban) and area restrictions (partial or total). It is not mandatory to provide this information, but it helps refining the candidate pre-selection.
4. Proposal of candidates for selected nodes: based on the previous information a set of candidates for network extension is proposed to the planning tool for each selected location. The following technologies are considered as candidate: batteries (Li-ion, NaS and flow), hydrogen, Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES), demand response (through flexible loads) and conventional network assets (AC lines and cables and transformers). In the case of lines/cables, the influence of updating one network branch is studied, to avoid that increasing the capacity in one segment to solve a congestion causes a new congestion in surrounding lines.

The environmental impact is modelled taking air quality impact, carbon footprint and landscape impact into account. A linearised air quality impact model has been developed which links the impact of CO₂, NO_x and SO_x emissions of conventional power plants to their production. These costs are modelled explicitly within the optimisation objective as the impact is dependent on the dispatch of conventional generation. The carbon footprint of candidate investments has been determined by means of a life-cycle-analysis considering the CO₂ emissions during the manufacturing and installation. The carbon footprint costs are considered as part of the CAPEX of the candidates. Finally, the landscape impact is quantified using an optimal routing algorithm [7]. The optimal routing algorithm uses spatial weights for installing transmission system equipment in certain areas, in particular existing infrastructure corridors, rural and urban areas, mountain regions and protected natural areas both onshore and offshore. These spatial weights are considered as part of the installation costs and using an A-star shortest-path algorithm [7], the optimal right of way for each candidate is determined as a minimum cost path. The developed approach is implemented as an open-source tool calculating optimal routes for both overhead and underground transmission as well as providing partial under-grounding solutions [8].

To keep the optimisation problem tractable, linearised power flow equations have been used for representing transmission and distribution networks. The well-known linearised ‘DC’ power flow approach is used for meshed transmission grids, including linearised formulations representing PST actions, point-to-point and meshed HVDC grids [5]. As opposed to meshed transmission grids, voltage congestion can occur frequently in radial distribution networks. As such, to model the voltage drop and the effect of reactive power on the voltage profile along radial feeders, the linearised DistFlow [9] approach is used to model radial networks.

The optimisation model uses generic storage and demand flexibility models, which can be parametrised based on the characteristics of particular technologies to be analysed. Using a dynamic storage model considering external energy inflow and energy dissipation, the state-of-charge of the storage system is modelled on an hourly basis. Charging and discharging efficiencies are considered in the optimisation. The demand flexibility model (Figure 2) considers voluntary and involuntary demand reduction as well as demand shifting conversing the total energy consumption over a given period. The parameters for the demand flexibility model are obtained through the FlexPlan pre-processor.

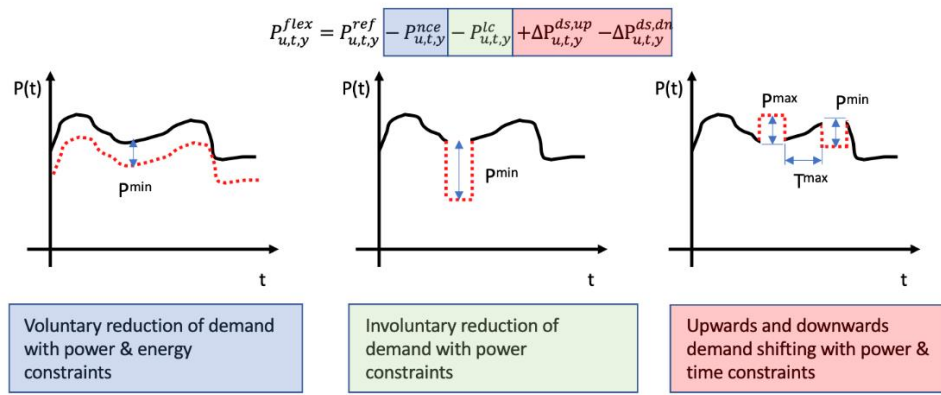


Figure 2 Generic demand flexibility model in FlexPlan

The FlexPlan model has been implemented as an open-source Julia / JuMP library as a proof-of-concept validation [10]. The library is built in a modular way, such that different modelling features, such as modelling of certain expansion options, application of decompositions, or deterministic vs stochastic solution of the optimisation model can be explored individually. The library also allows to interface to a variety of open source or commercial optimisation solvers for convenience.

IMPLEMENTATION OF THE PLANNING TOOL: SIMULATION ENGINE AND GRAPHIC USER INTERFACE

Based on the outcomes of the proof-of-concept using Julia / JuMP, the final version of the new FlexPlan grid planning tool is being developed as a robust cloud-based software. The new grid planning tool is implemented in an agile way using the Python programming language [11], starting from the core building blocks and iteratively increasing the scope with new advanced features.

The flow of the software and interactions between the FlexPlan grid planning tool and the candidate selection pre-processor can be summarized in four main steps:

1. the user inputs the data required to perform the grid planning simulation: the topology of the power system as of today, the asset technical characteristics and the future scenarios (time-dependent data related to loads, renewable generators and storage devices),
2. the planning tool performs a non-expanded optimal power flow in order to identify congested branches (assessed using Lagrange Multipliers associated to the branches' constraints and power flow directions), as well as the buses with high Locational Marginal Prices, suggesting the nodes which struggle to keep balance between intakes and off-takes, revealing technical opportunities for storage units,

3. based on the results of the previous step, the candidate selection pre-processor computes and provides a list of all promising possible network reinforcement candidates, storage asset candidates and flexible demand candidates,
4. the planning tool solves the grid expansion planning problem and finally outputs the network assets, storage elements and demand response programs selected to solve congestion issues while minimizing global system costs.

The optimization problem is solved using IBM ILOG CPLEX Optimizer [12], one of the leading mathematical programming solvers, modelled with the dedicated DOCplex Python Modelling Library [13]. Note that, in order to verify the accuracy of the implementation, the tool automatically asserts the results obtained with the cloud-based solution against the Julia proof-of-concept. The format used for input and output is JSON [14] with custom models following the standard OpenAPI 3.0 specifications [15], due to its flexibility, object-oriented nature and integration within the chosen implementation language. For future exploitation, handling of CIM/CGMES [16] files is considered. In order to guarantee the privacy of the data being processed by the FlexPlan grid planning tool, several security layers have been implemented. In particular, IP whitelisting and basic authentication are being used. Moreover, all data transfers are done using the HTTPS protocol.

The new FlexPlan grid planning tool is hosted on Amazon Web Servers [17] and can be accessed with two different ways: either through an HTTPS Application Programming Interface (API) which allow an easy interfacing with other tools or through an intuitive Graphical User Interface (GUI). The implementation of the GUI is done following a rigorous methodological process of User Interface (UI) and User eXperience (UX) design in order to build the right product for the future users.

Figure 3 shows some of the mock-ups developed as an outcome of the GUI design phase.

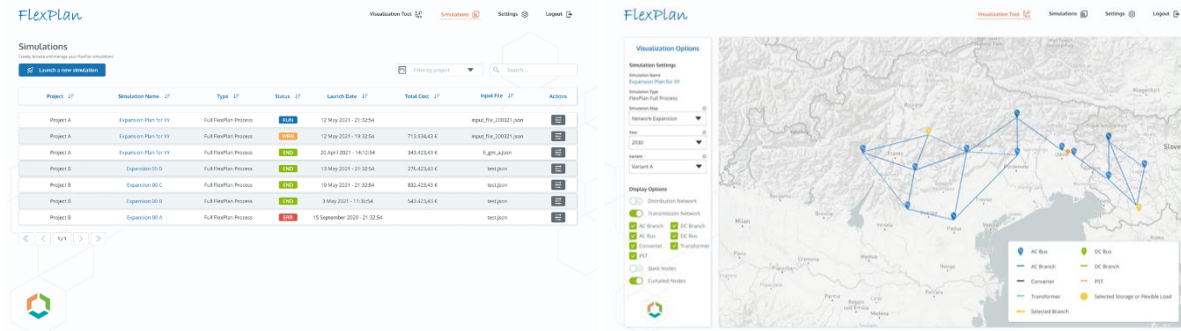


Figure 3: Mock-ups of the FlexPlan planning tool Graphical User Interface

THE SIX REGIONAL CASES: SCENARIOS AND FIRST SIMULATION RESULTS

The innovative grid planning tool developed in FlexPlan is validated within the project scope through its application to six regional cases. These were selected in order to represent realistically the different grid conditions in most of the European continent, as indicated in Figure 4.

The simulation of these regional cases is a highly complex activity from the computational perspective, given the large-scale nature of the considered grids and optimization possibilities (e.g. identification and comparison of grid expansion candidates). Thus, they present a sound way of testing the capabilities of the FlexPlan grid planning tool. Furthermore, by designing such large scale and realistic regional cases, FlexPlan aims as well to contribute to the identification of the role of flexibility solutions and creation of guidelines to cover possible regulatory gaps.

The creation and simulation of FlexPlan regional cases encompasses different activities related to data collection, processing and validation processes, based upon the creation of what can be considered as four main building blocks:

- Full scale transmission network models; [18]
- Synthetic representation of distribution network models

- Energy scenarios for 2030, 2040 and 2050 ensuring that Europe meets the established climate targets
- Full characterization of generation units and flexible loads.

The simulations in FlexPlan regional cases are built upon realistic, large-scale grid models with a one-to-one representation of grid nodes for transmission systems and a representative set of networks for distribution systems. Transmission grid is represented by using the European grid model used for the Ten-Year-Network-Development-Plan (TYNDP) 2018 studies, provided by ENTSO-E, as base dataset. The grid model received from ENTSO-E corresponds to a 2025 operational scenario. In this model, elements connected to 220 kV and above levels are modelled explicitly while branches and substations below this threshold might not be represented in detail, depending on the country analyzed [18]. Load values are represented aggregated by Extra High Voltage (EHV) connection point and embedded generation is connected to the next EHV or High Voltage (HV) node. The grid model was validated by the project team, through its conversion to a format allowing to carry out power flow simulations and was separated into the networks of the different regional cases, considering coherent border conditions for each one of them. This analysis also allowed to identify different data gaps, which had to be solved in order to adapt this model to the FlexPlan needs. These gaps included:

- Absence of grid models for Nordic countries (Norway, Sweden and Finland), which are required for the Nordic regional case;
- Absence of grid models at 150/110 kV voltage levels in different countries, together with absence of sub-transmission levels;
- Absence of geographic information data for grid nodes, which is a required input in the FlexPlan Tool (all nodes including generation units);
- Incomplete definition of type of generator units (thermal, wind, solar, etc).

These data gaps were solved through a comprehensive data collection process, resorting to data available at TSO/country level and also by using open-source data (e.g. Open Street Maps). The final grid models obtained for each regional case were validated in order to ensure their technical validity. Figure 5 depicts the example of the French transmission system after this process, where the difference between the model obtained from ENTSO-E (after adding geographic location of each grid node) and the final model to be used in the regional case is highlighted.

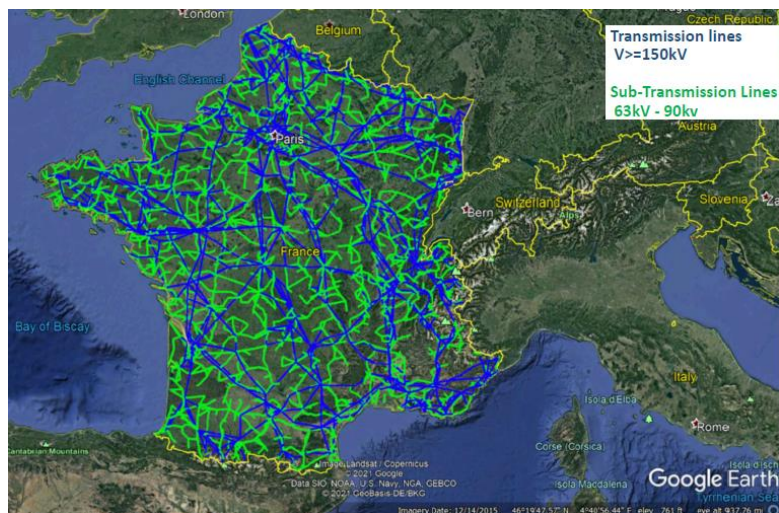


Figure 5 : French Transmission and Sub-Transmission Lines

Due to the lack of a European wide common dataset for distribution systems, and to the impossibility of building such a model, FlexPlan uses a different approach for modelling distribution systems. Here, synthetic networks are generated using an already validated methodology [19]. In order to create these synthetic networks, relevant statistics from representative network models (of real systems) are used, thus resulting in highly reliable distribution network models. These models are then reduced (reducing

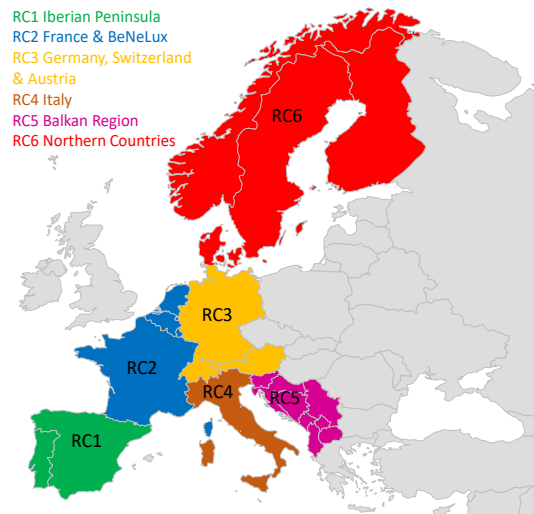


Figure 4: FlexPlan Regional Cases

the number of grid nodes), so as to keep the numerical tractability of the problem to be solved. These statistics are representative of distribution networks existing in the areas covered by FlexPlan. This results in the utilization of synthetic distribution network models, which are representative not only of each regional case, but also covering different geographical conditions (e.g. rural vs urban networks) within each country part of that regional case.

In order to provide a common scenario dataset for the long-term planning horizon for the regional cases, three different scenarios for three different target years are created, resulting in a set of nine different scenarios, which reveal different possibilities to achieve the climate targets defined by the European Commission. National scenario data is generated aligned to ENTSO-Es TYNDP 2020 datasets [20]. As these datasets do not contain data for 2050, data for this year is extrapolated based on a linear approach with further adaptations which take into account the European decarbonization trajectory comparing the linearly extrapolated data to scenario data for the year 2050 from ‘A Clean Planet for All’ report [3], which is a comparable source from the European Commission.

The derived scenarios provide data at a national level, but do not include information on the spatial and temporal availability of RES and usage of loads. However, these data are essential for the following grid studies, hence, national scenario data are spatially distributed to a transmission-nodal level and building on this, time series are generated. For this purpose, a regionalization methodology from the electricity market and transmission grid simulation framework MILES (Model of International Energy Systems) [21] is used and adapted to the context. The regionalization methodology distributes installed capacities taking into consideration statistical parameters based on socio-structural data, the distribution of existing plants, and information on land use. Knowing the installed capacities per node and their geographical location, time series for RES generation and load are calculated. The injection is calculated using historical meteorological data, characteristic models for the different technologies, as well as capacity factors for hydropower plants. Load time series are determined based on historical load profiles. The thereby determined yearly energy quantities are finally scaled to the amount of energy defined by the scenario data for the different types.

The temporal distributions of RES generation as well as load are highly dependent on meteorological conditions, which vary strongly between different climate years. To consider these uncertainties and ensure that networks operate reliably for different possible futures, a scenario generation and reduction approach is used. In a first step, Monte Carlo scenarios are generated by calculating RES injection and load for more than 35 historical climate years based on data from [22], [23]. Secondly, as the consideration of a high number of scenarios is a computational demanding task, the number of variants is reduced in order to determine a representative set of input data for the planning tool, while keeping their temporal and spatial correlation. The scenario reduction methodology clusters the Monte Carlo variants applying feature reduction and k-means clustering. Afterwards, one representative for each cluster is chosen, which is used as input data for the regional cases.

Furthermore, from the starting point of the regionalization results, European market simulations are executed, calculating the optimal dispatch of thermal power plants, storages, and cross-border flows for the considered countries. For this, the market simulation module of MILES [24] is used. The cross-border conditions enable to split the pan-European grid into the regional case studies, while ensuring coherent border conditions for the different regional cases. The overall methodology is briefly depicted in Figure 6.

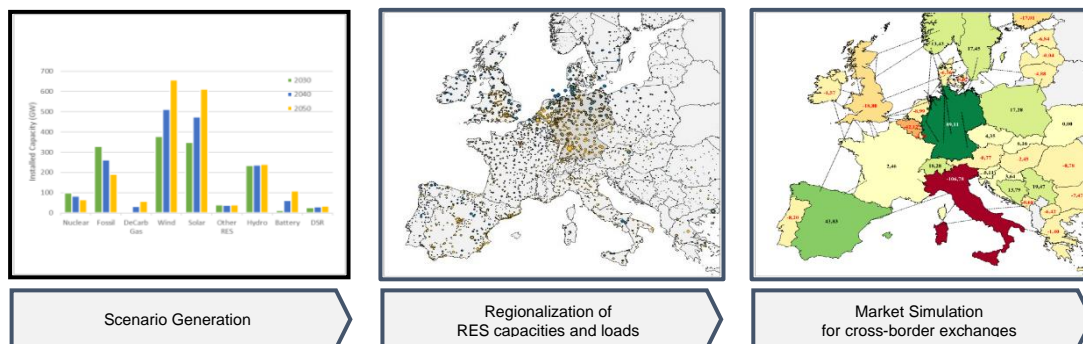


Figure 6: Methodology for modelling approach

In order to realistically represent the operational conditions of existing and forecasted European power system, the third building block of FlexPlan regional cases consists of a full characterization of generation and flexible loads. Most relevant generation units were identified, and a database was built, including relevant parameters as their location, installed capacity and fuel type. This database is built on top of the open-source database for generation units named “*powerplantmatching*”. Particularly for thermal power plants, and in order to assess their environmental impact, pollutant emissions data was also obtained, at plant level, and a dedicated emission model is being constructed to take the associated costs into account in the optimization problem [25]. Flexible demand is one of the technologies considered to play a major role in future flexibility needs. In the scope of FlexPlan, major flexible loads are identified and relevant parameters are considered, including their location and main characteristics allowing to characterize their flexibility potential. These include the utilization of Value of Loss Load and demand shift or reduction costs, which are calculated depending on the specificities of each country and taken into account available data at European or national level.

The first step of the simulation toolchain to take place in the FlexPlan regional cases considers the execution of Optimal Power Flows (OPF) to the energy scenarios in 2030, so as to identify grid expansion needs for the first target year. The simulation of a full-year, hourly time-series OPF is a highly complex activity, both from the preparation/validation of the involved data and the computational sides. In order to keep numerical tractability a methodology was implemented, allowing to decouple the yearly data into smaller periods but preserving the seasonality effects particularly relevant for hydro generation modelling. Using this approach, OPFs are solved in sequence for each selected period and the available energy content in hydro reservoirs at the end of each period is considered, in order to account for the typical seasonal effect of hydro. This modelling approach considers average weekly inflows, obtained from market simulation results already performed in the project scope as a proxy or from external data sources (e.g. TSO databases), and reference generation profiles to calculate the available energy content for each period within the year. Then the FlexPlan tool does the optimal dispatch of hydro units within the period timeframe considering the available energy. This approach assumes that flexibility provided by other technologies (e.g. storage units) is compensated throughout the period duration.

Preliminary results already obtained aimed at verifying the optimal period to be selected, allowing to ensure numerical tractability of the problem without reducing excessively the potential for flexibility. Two different periods have been tested: months and weeks. Monthly periods have been selected so as not to excessively limit the benefits of flexibility, as can be seen in Figure 7, where a comparison was performed between monthly (right) and weekly (left) periods. As can be seen, the stored energy in a hydro reservoir (and consequently the generation) is strongly limited to the target value (0.5 pu) if weekly periods are selected, thus reducing its potential to provide flexibility to the system.

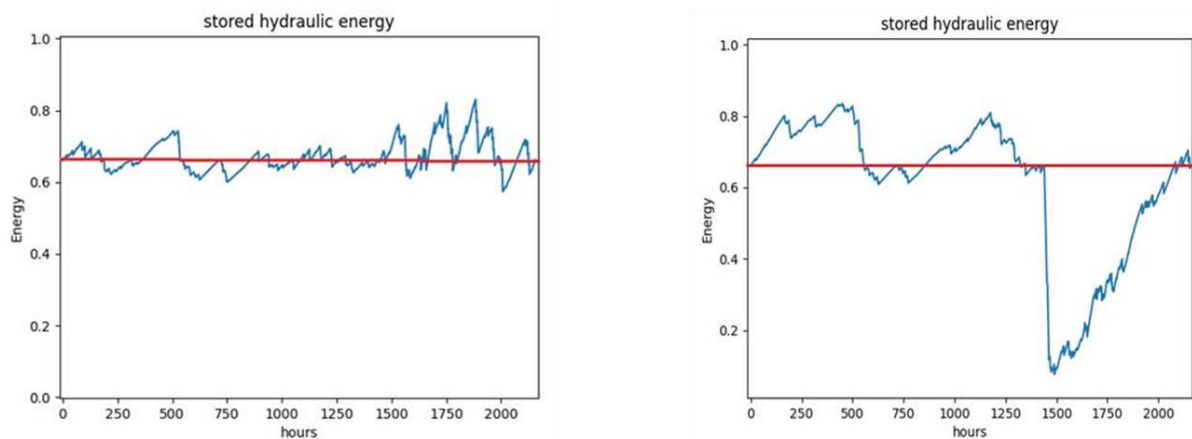


Figure 7 : Comparison between weekly and monthly optimization periods

CONCLUSION

Pursuing the Pan-European environmental goals prompts to bringing significant changes to the conventional power system. This creates new challenges which require to be solved with innovative methodologies. On this pathway, the EC proposes to include flexibility resources as a consistent part of

the network expansion planning and to consider demand response and storage with the same priority as generation in dispatching and re-dispatching procedures. This makes FlexPlan project highly relevant and timely both for testing new innovative grid planning methodologies and coping with the present challenges. Furthermore, the application of the FlexPlan methodology to six comprehensive regional case studies is capable to provide important learnings.

Including flexibility into grid planning requires a sound regular interaction between TSOs and DSOs both during the planning and subsequent operation phases. This requires commonly agreed and operative methodologies at least at national, but preferably at Pan-European level. However, a recent common TSO-DSO publication [26] points out that TSOs and DSOs still have radically different points of view on several important issues. One of the initial studies carried out by FlexPlan [27] listed several open issues, which, yet critical, have not been addressed yet, e.g. TSO-DSO priority in sharing of flexible resources or rules for allocation of costs and incomes in new common investment projects.

The common planning challenges for the System Operators call for establishing collectively agreed and universally accepted methods, as, for example, cost-benefit analysis, making possible to acquire shared planning priorities and goals. In addition, these methods should be further elaborated and clarified with regard to the already existing indicators e.g., VOLL or extended with new ones e.g., quantified environmental externalities, as it has been done in the framework of FlexPlan. Common methods should be developed and implemented and a consistent use of them should be enforced by the regulation for all Systems Operators, as it was done by ENTSO-E for the transmission grids. Uncertainty and especially absence of clear regulatory provisions is possibly one of the most significant barriers for establishing new services since this uncertainty could strongly discourage potential investors to develop the necessary infrastructure assets.

Another important learning is that the deployment of common modelling techniques will inevitably have to deal with the difficulties related to the overall complexity of data, especially regarding distribution grids or the opposite i.e., missing or/and erroneous data. Coping with it, the FlexPlan project has successfully tested several techniques as development of synthetic networks, which proved to be viable. In addition, decomposition techniques proved successful to preserve numerical tractability notwithstanding the huge dimension of the problem to solve.

BIBLIOGRAPHY

- [1] European Commission, “Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019,” 2019. [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L0944>
- [2] European Commission, “Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity,” 2019. [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0943>
- [3] European Commission, “A Clean Planet for All—A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy,” Nov. 2018. [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN>
- [4] ENTSO-E, “Revised methodology for assessing electricity infrastructure projects submitted to ACER,” Nov. 2019. [Online]. Available: <https://tyndp.entsoe.eu/news/2020/02/revised-methodology-for-assessing-electricity-infrastructure-projects-submitted-to-acer/>
- [5] H. Ergun *et al.*, “Probabilistic optimization of T&D systems planning with high grid flexibility and its scalability.” 2021. [Online]. Available: https://flexplan-project.eu/wp-content/uploads/2021/03/D1.2_20210325_V1.0.pdf
- [6] G. Migliavacca *et al.*, “The Innovative FlexPlan Grid-Planning Methodology: How Storage and Flexible Resources Could Help in De-Bottlenecking the European System,” *Energies*, vol. 14, no. 4, p. 1194, Feb. 2021, doi: 10.3390/en14041194.

- [7] H. Ergun, B. Rawn, R. Belmans, and D. Van Hertem, “Technology and Topology Optimization for Multizonal Transmission Systems,” *IEEE Trans. Power Syst.*, vol. 29, no. 5, pp. 2469–2477, Sep. 2014, doi: 10.1109/TPWRS.2014.2305174.
- [8] H. Ergun, *OptimalTransmissionRouting.jl - A software package to determine right of way*. Accessed: Oct. 12, 2021. [Online]. Available: <https://github.com/Electa-Git/OptimalTransmissionRouting.jl>
- [9] M. Farivar and S. H. Low, “Branch Flow Model: Relaxations and Convexification—Part I,” *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2554–2564, Aug. 2013, doi: 10.1109/TPWRS.2013.2255317.
- [10] H. Ergun et al., *FlexPlan.jl - Flexibility aware network planning model*. Accessed: Oct. 12, 2021. [Online]. Available: <https://github.com/Electa-Git/FlexPlan.jl>
- [11] G. Van Rossum and F. L. Drake, *Python 3 Reference Manual*. Scotts Valley, CA: CreateSpace, 2009.
- [12] I. I. Cplex, “V12. 8: User’s Manual for CPLEX,” *International Business Machines Corporation*, p. 596, 2017 1897.
- [13] IBM, *DOCplex Python Modelling Library*. [Online]. Available: <http://ibmdecisionoptimization.github.io/docplex-doc/>
- [14] ECMA, *ECMA - 404 The JSON Data Interchange Standard*. [Online]. Available: <https://www.json.org/json-en.html>
- [15] OPENAPI Initiative, *OPENAPI 3.1*. [Online]. Available: <https://www.openapis.org>
- [16] IEC, *Common Grid Model Exchange Standard*. [Online]. Available: <https://www.entsoe.eu/digital/cim/cim-for-grid-models-exchange/>
- [17] Amazon, *Amazon Web Services*. [Online]. Available: <https://aws.amazon.com/>
- [18] ENTSO-E, “Input grid datasets for the preparation of the TYNDP 2018.” [Online]. Available: <https://www.entsoe.eu/publications/statistics-and-data/#entso-e-on-line-application-portal-for-network-datasets>
- [19] G. Vigano, M. Rossi, C. Michelangeli, and D. Moneta, “Creation of the Italian Distribution System Scenario by Using Synthetic Artificial Networks,” in *2020 AEIT International Annual Conference (AEIT)*, Catania, Italy, Sep. 2020, pp. 1–6. doi: 10.23919/AEIT50178.2020.9241109.
- [20] ENTSO-E and ENTSO-G, “TYNDP 2020 - Scenarios Data,” Jan. 2020. [Online]. Available: <https://2020.entsoe-tyndp-scenarios.eu/download-data/>
- [21] J. Teuwsen, V. Liebenau, and C. Rehtanz, “Comparison of regionalization methods for network development planning,” in *IEEE PES ISGT Europe 2013*, Lyngby, Denmark, Oct. 2013, pp. 1–5. doi: 10.1109/ISGTEurope.2013.6695386.
- [22] S. Pfenninger and I. Staffell, “Renewables NInja.” <http://www.renewables.ninja>
- [23] M. De Felice, *ENTSO-E Hydropower modelling data (PECD) in CSV format*. Accessed: Dec. 10, 2021. [Online]. Available: <https://zenodo.org/record/3929773#.YbMYXi8w1N0>
- [24] C. Spieker, “Europäische Strommarkt- und Übertragungs- netzsimulation zur techno-ökonomischen Bewertung der Netzentwicklung,” TU Dortmund, Dortmund, 2019.
- [25] F. Gotzens, H. Heinrichs, J. Hörsch, and F. Hofmann, “Performing energy modelling exercises in a transparent way - The issue of data quality in power plant databases,” *Energy Strategy Reviews*, vol. 23, pp. 1–12, Jan. 2019, doi: 10.1016/j.esr.2018.11.004.
- [26] CEDEC, EDSO, ENTSO-E, Eurelectric, and GEODE, “TSO – DSO DATA MANAGEMENT REPORT,” 2019. [Online]. Available: https://docstore.entsoe.eu/Documents/Publications/Position%20papers%20and%20reports/entsoe_TSO-DSO_DMR_web.pdf
- [27] A. Morch, N. Amaro, and D. Siface, “D6.1 Guideline for the compliance of network planning tool with EU overall strategies and regulatory conditions,” 2020. [Online]. Available: https://flexplan-project.eu/wp-content/uploads/2020/04/D6.1_20200429_V2.0.pdf

C1 Power System Development and Economics

PS2 – Energy sector integration and tackling the complexity of multi-faceted network projects

Storage and Demand Response inclusion in the network extension planning process

Raúl RODRÍGUEZ-SÁNCHEZ*
TECNALIA R&I (BRTA)
Spain
raul.rodriguez@tecnalia.com

Santiago GARCÍA-LÁZARO
TECNALIA R&I (BRTA)
Spain
santiago.garcialazaro@tecnalia.com

Gianluigi MIGLIAVACCA
RSE SpA
Italy
gianluigi.migliavacca@rse-web.it

Dario SIFACE
RSE SpA
Italy
dario.siface@rse-web.it

SUMMARY

The increasing participation of variable wind and solar energy production plants in the power system requires flexibility from other resources, such as fast reacting generation assets, storage and demand response. Storage, other than pumped-storage hydropower, and demand response have not been considered in traditional network planning procedures, but they are expected to play a bigger role in the operation of power systems in the future.

In the frame of the EU FlexPlan R&D project (<https://flexplan-project.eu/>) an innovative network planning methodology is proposed, where flexibility resources are presented as candidates for network planning, competing with conventional network assets. The candidate pre-selection is carried out by a specific software tool developed to interact automatically with the main planning tool.

The consideration of relatively small size flexibility resources in the planning process, along with other aspects such as the environmental impact, the reliability, various scenarios and the interaction between distribution and transmission network operation, makes challenging the formulation and solution of the optimization function. Therefore, a pre-section of network extension candidates contributes to reduce the dimension of the mathematical problem.

The flexibility resources analysis is performed by the candidate pre-processor through the following steps:

- Network lines and transformers potentially affected by congestion are identified after performing an optimal power flow (OPF) simulation in the non-expanded network. The network model is evaluated under several generation and load scenarios. A ranking of congested branches is proposed based on hourly Lagrange multipliers' (LM) values.

- The flexibility resources analysis tool (pre-processor) proposes a list of network expansion candidates for identified congested assets, including storage (Li-ion, NaS and flow batteries, hydrogen, CAES and LAES), demand response (DR), and lines/cables/transformers. This selection is performed based on congestion characteristics and on possible location-related constraints. Cost and size details are provided related to the technology of each selected candidate.
- Eventually, the proposed candidates for grid congestion support are provided to the planning tool as input, which, in turn, assesses the best planning option for the power system in the time frame of the study.

Before proposing the candidate technologies, locational constraints and bus characteristics are checked. The network information provided for relevant nodes is used to discard, or not, some of the candidate technologies: urban substations, restricted areas, or the inexistence of loads, for example, already make some of them unfeasible. The characteristics of the congestion, such as the number of congestion hours in one year or the number of consecutive congestion hours are also an input for the selection of candidate technologies. A set of rules is predefined at the pre-processor to perform the assessment.

Once the most suitable technologies have been selected, the pre-processor estimates and provides a size and cost for each of them.

KEYWORDS

Storage - Demand Response – Electricity Network - Planning - Flexibility

INTRODUCTION: THE FLEXPLAN PROJECT

The increasing participation of variable wind and solar energy production plants in the power system requires flexibility from other resources, such as fast reacting generation assets, storage and Demand Response (DR) actions [1]. Storage, other than pumped-storage hydropower, and DR have not been considered in traditional network planning procedures, but they are expected to play a bigger role in the operation of power systems in the future.

To address this, the FlexPlan R&D project (www.flexplan-project.eu) was launched in 2019, financed under the European Union Horizon 2020 programme [2]. Its main objective is to establish a new T&D grid planning methodology considering the opportunity to install new storage devices, as well as to perform a flexible exercise of some loads located in selected grid nodes as an alternative to building new lines.

The specifications of the methodology and software to be developed try to meet several challenges:

- Consider an integrated planning of distribution and transmission networks at country and multiple country level.
- Assess environmental impact, targeting at air quality, carbon footprint and landscape restrictions.
- Optimize simultaneously several time-horizons (2030-2040-2050).
- Consider different meteorological variants in the analysis to account for weather variability throughout the years (scenario variants).
- Consider distributed flexibility resources (storage and DR) as network expansion candidates, together with conventional assets.
- Include investment decisions (candidates) through binary variables in the optimization model.

The requirements above result in a big size optimization problem, which becomes complex to solve because of its computational burden (details on the optimization function can be found in [3]). To limit the latter, decomposition techniques are used to divide the global problem in smaller sub-problems.

To support the planning problem, a software module has been created to reduce the number of network expansion candidates: candidate pre-processor (pre-processor from now on). Instead of considering every node 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. A “short” list of locations and technologies helps keeping the optimization problem tractable.

METHODOLOGY FOR FLEXIBILITY CANDIDATE SELECTION

The pre-processor software has been coded following a specification that gives response to the following aspects:

- 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 inputs by the user (network model and scenarios) and ends with the optimal grid expansion solution provided by the planning tool.
- The congestions in the system must be identified using the results of an Optimal Power Flow (OPF).
- Storage, DR and conventional assets should be proposed as candidate for network expansion, but depending on the characteristics of location and congestions, a pre-selection of technologies needs to be done to reduce the size of the problem.
- An estimation of size and price needs to be provided for every selected candidate, as input for the planning tool.

The whole planning process, where the candidate pre-selection is integrated, is illustrated in the following Figure 1. Three loops are necessary to carry out the complete procedure, so as to cover all three target years. The first step is to run an OPF simulation on a non-expanded electricity network model plus scenario for the first year of study, 2030 (which represents the 2020-2030 decade). With the results from the OPF and the inputs from the user, the pre-processor provides a set of candidates for network expansion for year 2030. Then, the planning tool runs the optimization process and the resulting network becomes the non-expanded model for 2040 and it will be the input for the second loop. In the final step, the planning tool will provide the optimal network expansion for the whole period under study (2030 to 2050), choosing among all the candidates proposed by the pre-processor in the three loops.

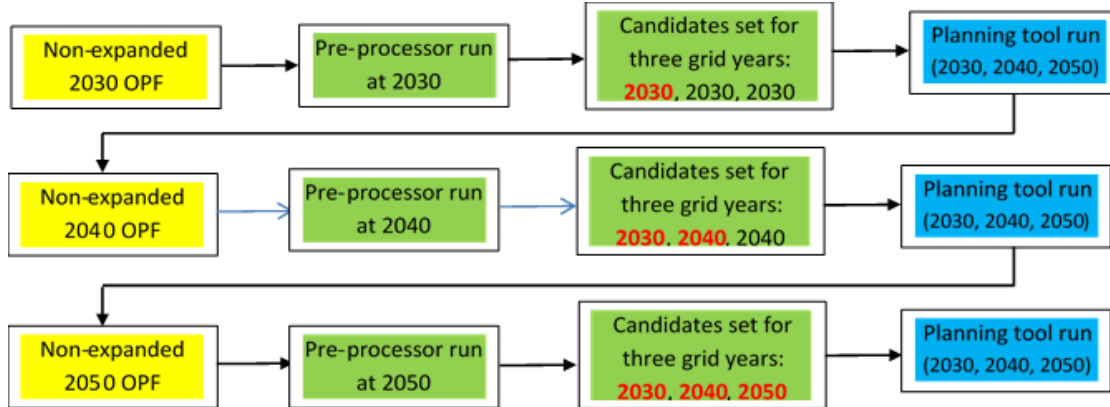


Figure 1 Integration of planning tool and pre-processor

To meet the rest of the points of the specification above, a methodology was defined for the pre-processor, consisting in four main steps: analysis of congestions, node and branch selection, check of constraints and characteristics, and selection of the set of candidates. These steps are detailed in the next two sections and are summarized graphically in the next Figure 2.

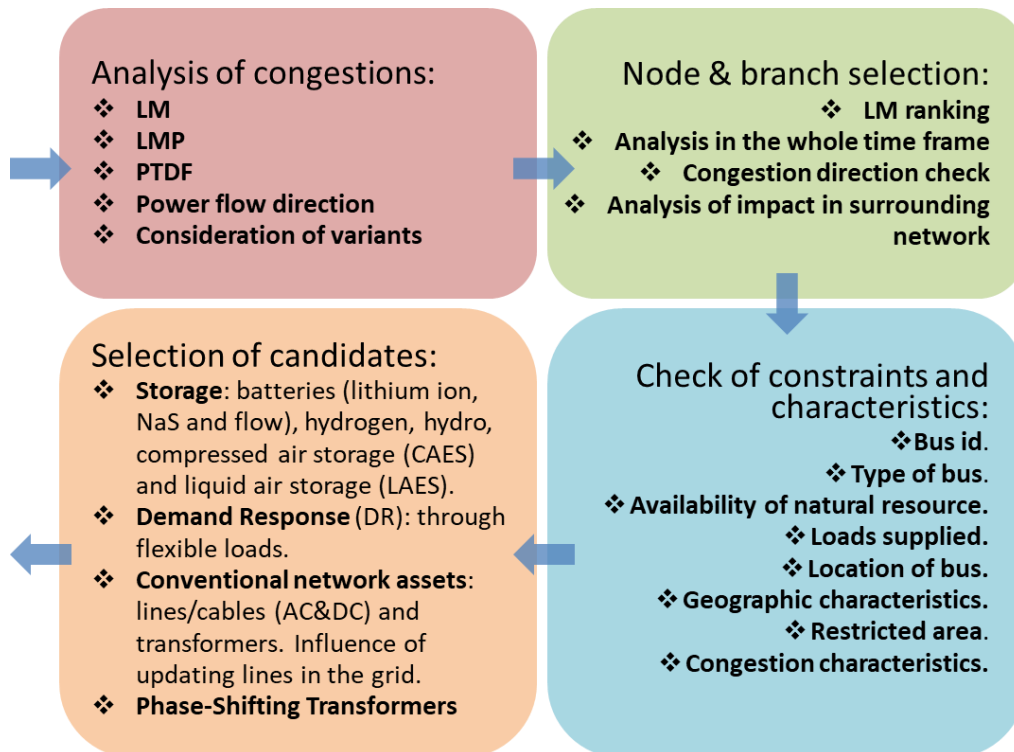


Figure 2 Main steps for pre-processor methodology

SELECTION OF CONGESTION SCENARIOS AND LOCATIONS

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 result below or at the capacity limits of each network asset, i.e., they are not an indication of congestion (see Deliverable 2.1, at www.flexplan-project.eu). By contrast, four types of inputs are provided by the OPF solver which are used by the pre-processor:

- Lagrange Multipliers constraints (LM) of branches are a direct outcome of the solution of the optimization problem (OPF) [4]. They provide information about the dispatching cost reduction obtained by sending an additional MW of power through a branch. Therefore, they permit to identify congested lines: these lines will be characterized by non-zero LM values and such value will correspond to the objective function cost reduction deriving from one unit increase of the line transit limit.
- Locational Marginal Prices (LMP) show the dispatching cost variation to accommodate a unit increment of demand at a bus [5][6]. They provide useful information for the location of flexible resources (storage and DR).
- Power flow values of branches provide information about the direction of the flow of energy and about their saturation level, in relation to their rating.
- The Power Transfer Distribution Factors (PTDF) represent the change in the active power flow through network branches, as a consequence of transferring one extra power unit between two nodes at given grid [7].

In a year-long simulation, the OPF provides a value, for the first three parameters in the list above, for each of the 8760 hours and for each of the buses and/or branches, in form of matrices. The PTDF is dependent on the topology and, therefore, there is a unique value for the whole year (no topology changes are considered before the expansion).

In a first step, the pre-processor checks the LM matrix with the results of the OPF, for the grid model under study and various scenario variants for each year (3 to 5 meteorological variants). The LM value evolution along the year is analysed statistically, but two main values are considered to reflect the following:

- Congestion occurrence: number of hours in a year, when the LM value is different from zero.
- Congestion severity: average LM value considering all year hours (sum of LM values for a branch, along a year).

These two values are considered together in a factor that result from their multiplication, i.e., occurrence times severity. For each year under study, this is done for all scenario variants, and a common ranking is created for all the branches 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, branches are selected, starting from those with higher values (the number of candidates is a parameter for the software). These selected branches reflect the most congested lines 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 or cable).

For each of the selected congested lines, the characteristics of the congestion are analysed in a more detailed way:

- Power flow direction: it is studied for the whole period, to check whether the congestions occur in one or two directions and the probability of that occurrence.

- Number of congestion hours: the number of hours that a branch is congested throughout a year is counted.
- Consecutive congestion hours: the number of consecutive hours that a branch is congested within a year is calculated, this affects both sizing and performance of storage systems.

This information is used in the next steps of the methodology to help select the best flexibility options.

CHECK OF CONSTRAINTS AND SELECTION OF FLEXIBILITY CANDIDATES

The pre-processor aims to propose 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:

- 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).

All technologies above are considered as possible candidates for network extension, competing with conventional network assets. In the frame of FlexPlan, these technologies have been characterized and results of that characterization are available in Deliverable 2.2 (www.flexplan-project.eu).

Two ways are possible to propose candidates to the planning tool: forced by the user and automatically calculated by the candidate pre-processor module. In the first case, the user, based on the knowledge about the network, proposes network extension candidates. This is specially recommended when:

- The network needs to be extended between nodes that are not connected through lines or cables in the non-expanded scenario.
- Technologies require a dedicated study for their installation, e.g., HVDC, phase shifting transformers (PST) and pumped-hydro, which are designed specifically for a location.

Forced candidates have preference in the candidates' list that the pre-processor provides to the planning tool. Candidates calculated automatically by the pre-processor are added after them depending on their position in the ranking.

In the latter case, 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: the network information provided for nodes and the congestion characteristics 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, grouped in areas, to each of the nodes (buses) of the grid model:

- Type of bus: substation (air, air-compact, underground); Industrial load (metal, paper, textile, cement, water treatment, gas industry, mining, shipyard, high speed train, automotive, chemical, other); power plant (wind, PV, solar, thermal coal, CC, biomass, hydro, nuclear); commercial load (airport, other).

- Availability of natural resources (for substation type buses): water (river, reservoir); wind (area with wind parks near); sun (solar power plants near); cavern; biomass.
- Loads supplied (for substation type buses): residential (mainly); commercial (mainly); industrial (mainly); mixed (lower voltage level networks, sub-transmission/distribution); big industrial (as above).
- Location of bus: urban (populated city); industrial area; semi-rural (outskirts of populated city, small city); rural.
- Geographic characteristics (for rural buses): mountainous; plain
- Restricted area (not allowed to build new installations): for lines; for hydrogen; for batteries; for CAES/LAES; total restriction.

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 (it is advised to include it in a second round, after congestions have been identified). When a node or branch is selected for the installation of a new flexibility resource or network asset, bus and congestion characteristics are checked, to assess the suitability of each of the candidate technologies. 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. For example, if a congestion tends to last more than six hours, batteries or demand response strategies might not be the best flexibility candidates to relieve a congestion.

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.

The candidate selection process has aspects common to all technologies but also some differences related to them:

- Storage: from the congested branch, the node with higher LMP is preferred as location, because it indicates a higher cost avoided for the system to supply demand at that point. LMP values need to be checked for all the hours simulated. The power of the storage candidate is proposed in relation to the rated capacity of the congested branch and its energy capacity in relation to the maximum number of consecutive hours of congestion, or to the maximum yearly congestion hours, depending on the technology.
- Demand Response: the first action is to check if a load exists at any the congested branch nodes. If that is the case, it is checked if the load is already flexible, if not, we assume that it can be made flexible. If the load is characterised with a type and there exists a percentage of flexibility assigned to that type of load, this value is considered. If there is not, a general percentage is considered, which is lower than the previous. Then, the “size” of the DR is related to its flexibility. The cost of DR is a very difficult value to assess, so some estimation is provided, however, it is recommended to use this parameter to perform sensibility analyses.
- Line/cable: candidates are proposed with the same characteristics of those of the congested asset. The cost of the line, cable or transformer is proposed based on literature values.

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 affect the saturation in other lines.

Given a congested line LC , we consider an injection of power in node K_1 and the extraction of the same power in K_2 . The line power constraints are relaxed so that line transits can go over the rated capacity of the line.

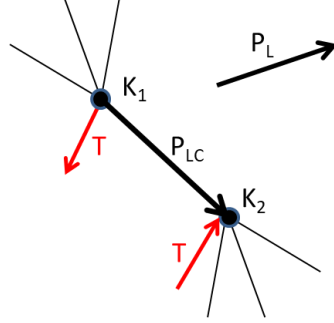


Figure 3 PTDF analysis approach

Following the definition of PTDFs, we calculate the power flow modification as result of this new power exchange (T), in both the congested line (lc) and a surrounding line l :

$$P_l - P_l^0 = T(PTDF_{K_2,l} - PTDF_{K_1,l}) \quad (1)$$

$$P_{lc} - P_{lc}^{max} = T(PTDF_{K_2,lc} - PTDF_{K_1,lc}) \quad (2)$$

Combining the previous equations, we obtain a relationship between them. We consider the case when the saturation of line l occurs ($P_l = P_l^{max}$; $P_{lc} = P_{lc}^*$).

$$P_{lc}^* - P_{lc}^{max} = \frac{(PTDF_{K_2,lc} - PTDF_{K_1,lc})}{(PTDF_{K_2,l} - PTDF_{K_1,l})} (P_l^{max} - P_l^0) \quad (3)$$

We define the parameter $\alpha_{l,lc}$, which represents the oversaturation in line lc when line l gets saturated.

$$\alpha_{l,lc} = \frac{P_{lc}^* - P_{lc}^{max}}{P_{lc}^{max}} = \frac{(PTDF_{K_2,lc} - PTDF_{K_1,lc})}{(PTDF_{K_2,l} - PTDF_{K_1,l})} \frac{(P_l^{max} - P_l^0)}{P_{lc}^{max}} \quad (4)$$

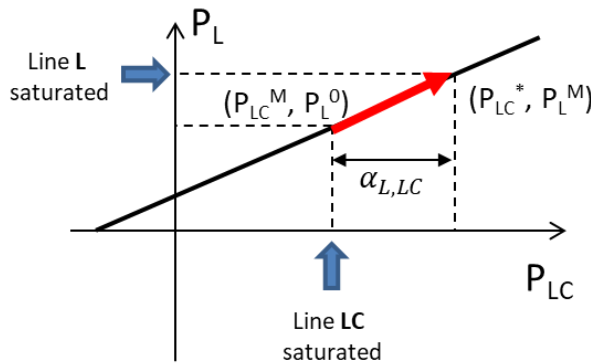


Figure 4 Relationship between the saturation of the congested line and of a line in the influence area

The lines with higher risk to become congested are those with lower values of $\alpha_{l,lc}$. To avoid congestion problems in other points of the network, they should be expanded alongside the congested line identified in the first place. In this way, an expansion corridor is created. To cope

with this, the pre-processor calculates the saturation factors, α , of all branches and adds those with lower values, if any, as candidate for expansion.

FIRST VALIDATION OF RESULTS

One of the tests of the pre-processor was performed using the IEEE 6-bus system, as defined in [8]. The input files used by the pre-processor were the following:

- Grid and scenario input files for the planning tool: it is a grid with six AC buses, four AC branches and two DC branches.

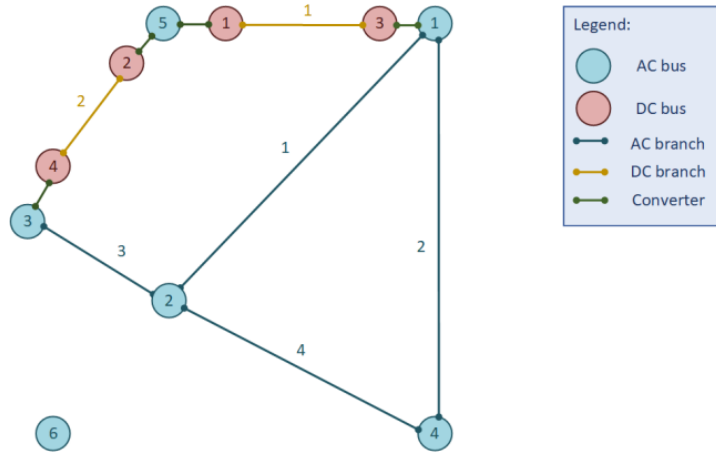


Figure 5 IEEE 6 bus system

- OPF Output file from the FlexPlan planning tool, including: AC power flows in branches, LM values for branches, LMP values for nodes and PTDF matrix. LM values were nonzero in branches 3 and 4 for certain hours, which means that they had some sort of congestion in that period. However branch 4 had very small values (under 10^{-10}). Branch 3 in the model shows high congestion and its LM values are represented in the following Figure 6.

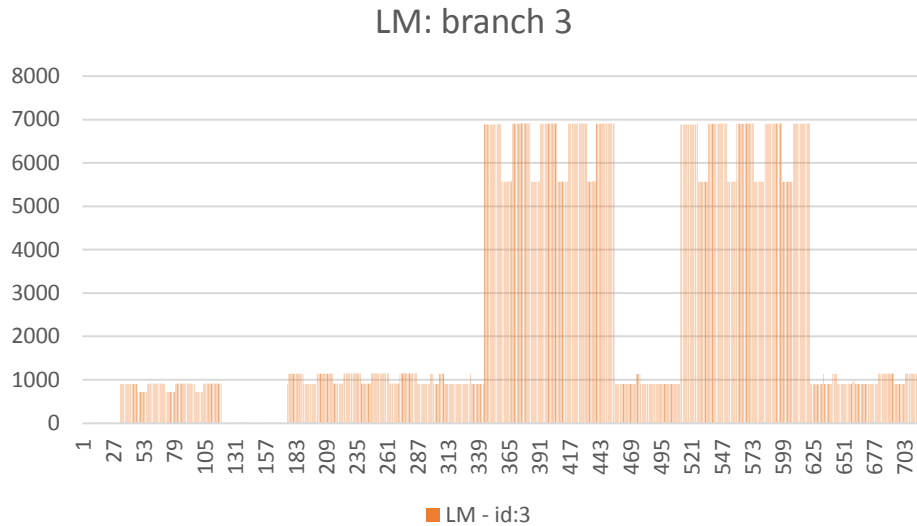


Figure 6 LM values of branch 3 of the IEEE 6 bus system (output from the FlexPlan planning tool)

Considering the previous inputs, the pre-processor provided the following candidates for network expansion:

- Lines AC and DC for branches 3 and 4. Even if the SW allows to establish a limit for LM value consideration, in this example, this was set to zero, so all nonzero values were

considered as congestion. In addition, branch 1 was also selected as candidate due to the influence of one of the other branches.

- Two storages were proposed as candidate by the tool in node 2, one because of branch 3 and the other because of branch 4. Only one technology was selected, hydrogen, and this can be explained because of the duration of congestions, which makes not possible the use of batteries or LAES. Also, buses were not totally characterized, and, in this case, there was no information about cavern availability, so CAES was not a candidate.
- A flexible load was proposed in bus 2, because a load characteristic was introduced in that bus to test the tool.

The figure below shows an equivalent of Figure 6, calculated by the pre-processor tool..

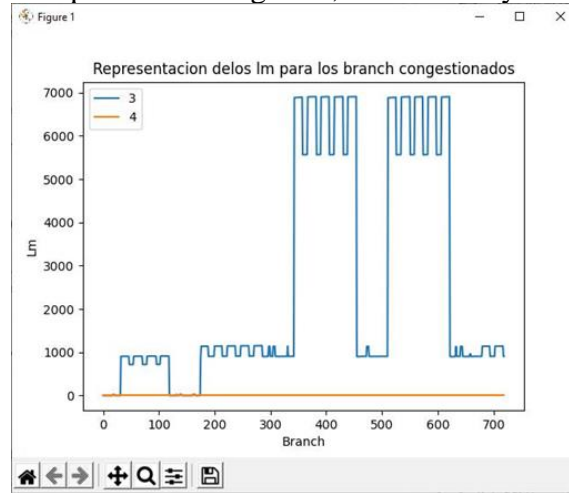


Figure 7 LM values of branch 3 of the IEEE 6 bus system (output from the pre-processor)

The following figure shows the congested lines in a map, considering that a location (longitude and latitude) was provided to each of the buses. The debug mode of the pre-processor permits such a graphical analysis.

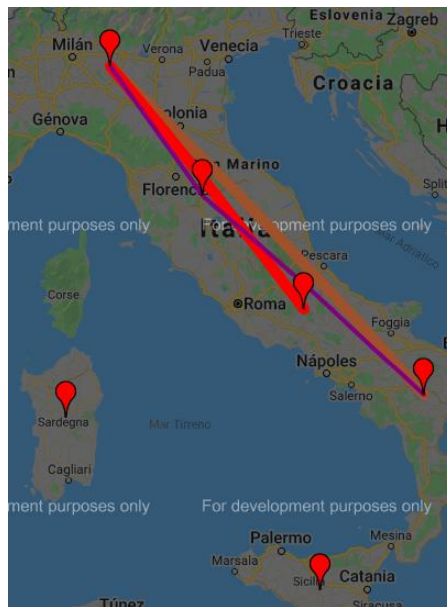


Figure 8 Map showing congested branches (red and orange)

CONCLUSIONS

Flexibility resources such as storage (big water reservoirs excluded) and demand response (DR) are expected to play a major role in the future, driven by the expected increase of the electrification of the energy system and of the high share of renewables in the energy mix. The need of flexibility will affect the short term operation of electricity networks and this should be reflected, in advance, during the planning process of future grids. Currently, distributed resources are not normally considered at the planning stage.

A methodology and a software have been developed in the frame of the FlexPlan project aiming to consider storage and DR as network extension candidates at the planning stage. The characterization of flexibility providing technologies, together with a standard OPF simulation, permits to conduct an automated assessment of expected congestions in the grid and a proposal of network extension candidates. The extended characterization of the network buses, including restrictions and additional data on the location, allows a better selection of technologies. However, the user is also permitted to input candidates based on its knowledge about the network.

To allow an automated assessment of candidates, technologies need to be characterized in a proper way, both from the technical and economical standpoints. Dealing with extensive areas of network involves many different realities (energy demand characteristics, energy mix, network infrastructure, regional policy and regulation, etc.), still, average values need to be considered for characterization, to make the problem tractable. Therefore, using sensibility analyses for some key performance indicators (KPI), is foreseen as a requirement. Some parameters are uncertain, either because they are linked to currently non-deployed technologies or markets, or just because the evolution of climate, raw materials, country politics is hard to foresee, specially, when we look at distant time horizons. Some of the parameters that we consider suitable for sensibility are, for example, the cost of the demand response, the availability of flexibility by demand response and the evolution in the cost of batteries.

The pre-processing of network expansion candidates turns out to be an adequate approach to help make extensive planning optimization problems tractable.

BIBLIOGRAPHY

- [1] European Commission. “A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy” (COM(2018) 773 final, Brussels, 28.11.2018)
- [2] European Commission. “Horizon 2020” [online: <https://ec.europa.eu/programmes/horizon2020/en/home>, last accessed: 12/01/2022]
- [3] G. Migliavacca et al. “The Innovative FlexPlan Grid-Planning Methodology: How Storage and Flexible Resources Could Help in De-Bottlenecking the European System” (Energies, vol. 14, no. 4, doi: 10.3390/en14041194, February 2021, page 1194)
- [4] H. Liu, L. Tesfatsion, A. Chowdhury. “Locational marginal pricing basics for restructured wholesale power markets” (Power & Energy Society (PES) General Meeting, 2009. IEEE, Calgary, 2009)
- [5] L. Chen, H. Suzuki, T. Wachi, Y. Shimura. “Components of nodal prices for electric power systems” (IEEE Transactions on power systems, vol. 17, no. 1, 2002, pages 41-49)
- [6] Q. Wang, G. Zhang, J. D. McCalley, T. Zheng, E. Litvinov. “Risk-based locational marginal pricing and congestion management” (IEEE transactions of power systems, vol. 29, no. 5, 2014, pages 2518-2528)
- [7] D. Huang. “Dynamic PTDF implementation in the market model” (Delft: Delft University of Technology, Faculty of Electrical Engineering, Mathematics and Computer Science, 2001)
- [8] L. Garver. “Transmission Network Estimation Using Linear Programming” (IEEE transactions on power apparatus and systems, vol. 89, no. 7, 1970, pages 1688-1697).

Planning of distribution networks considering flexibility of local resources: how to deal with transmission system services

Marco Rossi^{1}, Matteo Rossini¹, Giacomo Viganò¹, Gianluigi Migliavacca¹,
Dario Siface¹, Izabella Faifer¹, Hakan Hergun², Iver Bakken Sperstad³*

¹Ricerca sul Sistema Energetico - RSE SpA, Milan, Italy

²KU Leuven, Leuven, Belgium

³SINTEF Energy Research – SINTEF Energy Research, Trondheim, Norway

*marco.rossi@rse-web.it

Keywords: DISTRIBUTION NETWORK PLANNING, LOCAL FLEXIBILITY, STORAGE, TRANSMISSION NETWORK PLANNING, ANCILLARY SERVICES

Abstract

Modern planning techniques for distribution systems consider, in addition to the conventional grid reinforcement, the provision of power flexibility from local resources. This solution is demonstrated to be cost-effective in numerous cases. However, distribution resources might be required to provide services to transmission system too, and this aspect needs to be considered within the selection of the best distribution planning options. This paper investigates a distribution network planning strategy based on different trade-offs between “minimization of investment costs” and “maximization of distribution flexibility for transmission services”, which is aimed at supporting a cooperative (but decoupled) planning for both distribution and transmission systems.

1. Introduction

The evolution of power systems introduces new challenges in terms of operation and planning, and current research is demonstrating how local services (provided by flexible demand/generation/storage) can compete with the conventional network reinforcement at any voltage level. In fact, literature [1]-[8] proposes many distribution network planning strategies aimed at determining the best trade-off between local flexibility and new lines/transformers. All of them are clearly showing how the current practices (based on manual procedures and worst-case scenarios analysis) are not leading to optimal solutions. On the contrary, the adoption of dedicated optimization techniques (based on time series processing and multiple scenario analysis [1][2]) assists the selection of the most cost-effective planning option for the solution of local problems.

Nevertheless, distribution network resources have the potential of providing services to the transmission system too and this is a standard requirement already (especially in terms of curtailment of renewable generation [3]). This means that distribution system operators might be required to operate/plan their network in order to guarantee a given amount of local flexibility for transmission services [4]-[6]. However, there is an evident and unexplored conflict between:

- the minimization of the costs related to local congestion management and
- the maximization of the distribution flexibility that can be exploited for transmission services.

For this reason, numerous research initiatives [9][10] and working groups [1][3][5] are suggesting enhanced cooperation among transmission and distribution operators, having the objective of minimizing the operational and planning costs for the entire system [7].

The absolute optimal planning solution, which considers the necessities of the system at any voltage level simultaneously, can be achieved by merging the models of transmission and distribution systems in a single, joint optimization problem. However, in addition to requiring a significant (and probably unbearable) computational burden [2][8], the lack of transparency and standards to exchange information among system operators is one of the barriers for a joint planning of transmission and distribution networks [1].

Having considered the challenges discussed above, this paper proposes a procedure for distribution network planning which, in addition to the solution of local issues, guarantees:

- the consideration of potential transmission system requirements in terms of ancillary services, by trading-off investments cost and exploitable flexibility;
- facilitated negotiation between transmission and distribution operators for the selection of planning options which meet the requirements of both the systems, with no exchange of detailed network information.

2. Case study and network model

In order to illustrate the planning strategy, the European configuration for the CIGRE Medium Voltage distribution network benchmark [11] has been adopted as reference. In

particular, all the switches have been considered to be operated in their normal state and the capacity of the grid lines are selected to be 6.5 MVA for underground cables and 5.5 MVA for overhead lines.

2.1. Modifications of the standard benchmark case

The case study focuses on the solution of the planning problem, having considered the availability of local storage units for the provision of congestion management services. For this reason, all the remaining loads and generators are assumed to be non-dispatchable and to feature the 1-day power profiles suggested by [11].

The considered distribution network, in its current configuration, is not subject to any congestion risk. For this reason, the planning problem is studied having supposed an increased wind generation (connected to bus 7), from the existing 1.5 MW to 9 MW. Finally, an additional storage unit is assumed to be connected to bus 14, such that the entire system features:

- a 0.6 MW – 1.2 MWh storage unit on bus 5;
- a 0.2 MW – 0.4 MWh storage unit on bus 10;
- a 1.0 MW – 2.0 MWh storage unit on bus 14.

All these units are assumed to have a 90% efficiency during both the charging and discharging phases, and a 0.1% hourly self-discharge rate.

2.2. Planning candidates

The operation with 9 MW wind power is not feasible within the considered system: some lines would be significantly overloaded and voltage problems may occur if not properly managed (reactive power flexibility of generators and tap changing transformers are assumed to be adjustable at no operational cost). In order to face the possible congestions, the following planning candidates have been foreseen:

- Each existing branch can be reinforced by an alternative line/transformer characterized by twice its conductance and capacity (this is equivalent to the installation of two branches in parallel). The cost for line reinforcement is assumed to be equal to:
 - 150 k€/km for underground cables;
 - 60 k€/km for overhead lines;
 - 350 k€ for (50 MVA) transformers.
- Each existing storage can be doubled in rated power and capacity, having considered investment costs equal to 350 k€/MWh.

In addition to these candidates, flexibility of existing storage is also considered by the planning procedure. According to that, their related operational costs are included within the objective function and depend on the wholesale energy price, which is assumed to be equal to 50 €/MWh over the entire planning horizon.

The case study is limited to few simple candidates, aimed at returning intuitive and easy to be interpreted results. In fact, the paper focuses on the proof-of-concept for the proposed methodology, which can be anyway applied to more complex situations and sets of possible investments.

2.3. Model of upgradable distribution network

The planning of a distribution network consists of the selection of the grid expansion options (new lines and transformers) and flexible units (dispatchable storage) which guarantee the minimum capital and operational expenditures for the solution of existing or potential issues. Therefore, it can be formulated as a classical optimization problem and, since binary investment decision variables needs to be managed, a (mixed-integer) linear formulation is the preferred option [2], especially for large power systems which can be also characterized by a significant amount of expansion candidates.

Given that voltage is one of the electrical quantities to keep under control for distribution network operation and planning [12], a linear approximation of the AC Optimal Power Flow (OPF) is adopted [13]. Thanks to this formulation, which is recognized to be accurate for conventional Medium Voltage distribution grids, a computational efficient algorithm can be easily coded and processed for the planning options described in the following section.

3. The proposed planning strategy

As anticipated above, there is conflict between the minimization of the planning costs (limited to distribution network needs) and the delivery of power flexibility to the transmission network. For this reason, the proposed strategy is based on the iterative exploration of a number of possible planning options which cover different trade-offs in terms of costs for local network investments and available capacity for transmission services. Each option consists of the result of more optimization problems, which can be sequenced in different ways. The proposed strategy can be summarized with the three main steps described in the following subsections.

3.1. Step 1 – Minimization of the planning costs for distribution network

The most intuitive and common procedure for the planning of distribution system consists of minimizing the operational and investment costs for the solution of local network issues, regardless of transmission potential needs. For the considered case study, the objective function is composed by two terms:

- Storage operation cost, which results from internal losses and energy price. The resulting cost is re-scaled to consider a 10-year lifespan (having assumed the investigated 24-hour time slot to be recurrent).
- Line/transformer/storage investments, which actual costs are reported in section 2.2.

By processing the optimization problem for the considered case study, the returned solution can be summarized as:

- upgrade of the lines connecting buses 3-8 and 7-8;
- operation of existing storage units connected to bus 5 and bus 10, for congestion management services;
- total operational + investment costs of about 245 + 446 k€.

In fact, looking at the results reported in Figure 1, the loading of the substituted lines is exceeding the initial 6.5 MVA capacity during the wind production peaks.

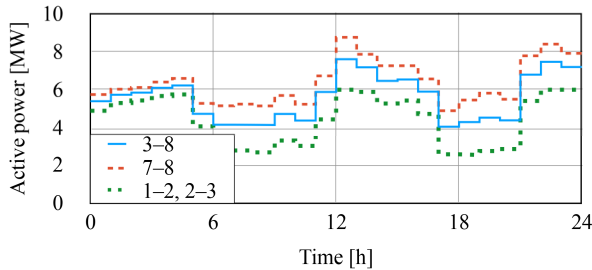


Figure 1. Loading of lines originally subject to congestion risk when step 1 candidates are selected.

Optimization results clearly indicate that also storage units are contributing to the reduction of network issues. Looking at their power exchange profiles (Figure 2), the existing units connected to bus 5 and bus 10 are absorbing active power in order to prevent the congestion of the lines connecting bus 1-bus 2 and bus 2-bus 3 (Figure 1).

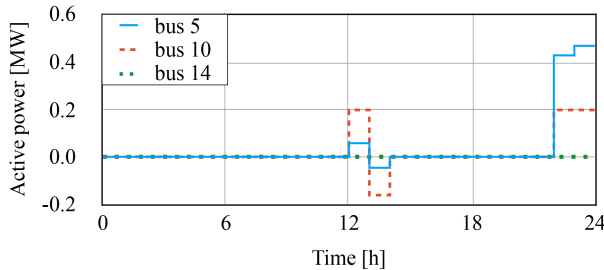


Figure 2. Active power exchanged by existing storage units when step 1 candidates are selected.

Once the optimal investments have been defined, the portion of local flexibility remaining from the local congestion management can be used for services supporting the operation and planning of the upstream transmission network. This portion can be quantified by fixing the selected investments and running two separated OPF routines with the following objective functions:

- maximization of the active power import from transmission to distribution system;
- maximization of the active power export from distribution to transmission system.

Although the implementation of this optimization problem seems to be intuitively correct, the solution of the proposed OPF with these objective functions can be misleading. In fact, the constraints in terms of storable energy limit the maximum power that can be delivered by the storage units in a given time period. Since storage flexibility can be requested anytime for transmission services, the removal of inter-temporal constraints (i.e. energy accumulation) is meaningful for this optimization step. This means that storage units are temporarily modelled as dispatchable devices, featuring the same power capability.

Figure 3 reports the result of these two optimization routines, which makes evident the availability of a power flexibility

bandwidth around the baseline profile resulting from the cost-minimization problem.

In order to evaluate, for each storage unit, the portion of available flexibility that can be exploited for transmission services, the power profiles obtained from these three optimization procedures are compared (Figure 4).

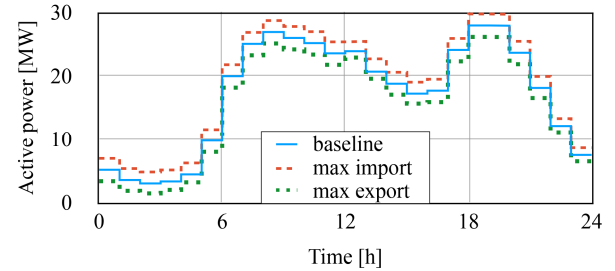


Figure 3. Possible active power exchange profiles between distribution and transmission system when step 1 candidates are selected.

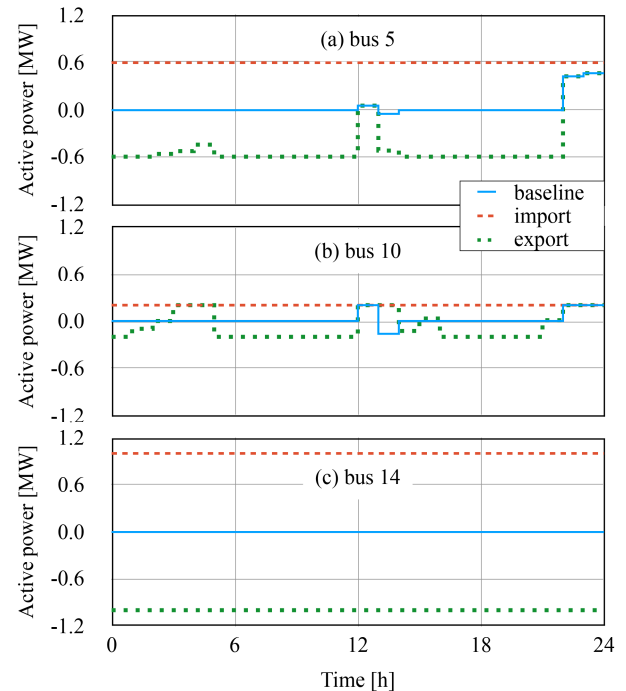


Figure 4. Storage units active power profiles returned by the step 1 of the proposed planning procedure.

From their analysis, it can be clearly recognized that:

- Storage units connected to bus 5 and bus 10 are involved in local services and cannot be considered constantly available for other purposes. In fact, maximum import/export profiles overlap the baseline in case of local congestion.
- Storage unit connected to bus 14, instead, can be exploited in its full power capability, since the obtained profiles result to be flat, i.e. not affected by distribution services and bottlenecks.

In conclusion, having considered that local congestion management is not generally correlated to reserve needs at

transmission level, the unit connected to bus 14 represents the only reliable resource capable of providing flexibility services to the upstream network. Therefore, in case this planning option is selected, the transmission system would see a single equivalent storage unit, featuring 1.0 MW active power capability and 2.0 MWh storable energy.

3.2. Step 2 – Maximization of distribution network energy export/import

Another interesting planning option consists of identifying the network investments capable of maximizing the exploitability of local flexible resources for transmission services. The solution to this problem is obtained by using a similar procedure but reversed with respect to the previous step. In this case, the maximum power export/import profile is defined before the selection of the planning investments, and it is obtained by running (again) two separated OPF routines with the following objective functions:

- maximization of the active power import from transmission to distribution system;
- maximization of the active power export from distribution to transmission system.

Contrarily to step 1, planning candidates are freely selectable within this optimization problem, guaranteeing the maximum power flexibility transfer to the upstream network (at any cost) achieved. Figure 5 demonstrates that a significantly larger regulation bandwidth can be achieved around the baseline profile (which is calculated later in the process).

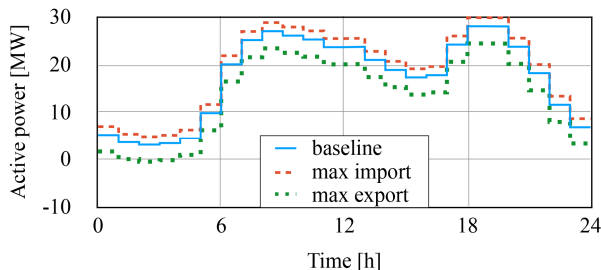


Figure 5. Possible active power exchange profiles between distribution and transmission system when step 2 candidates are selected.

According to the adopted objective functions, investment costs are not influencing the selection of the available candidates. For this reason, some of them can be built even if they are not contributing to the achievement of the maximum power export/import. Therefore, a further OPF problem is solved by minimizing the investment costs, having imposed a power exchange with the transmission network equal to the maximum export/import profile. Thanks to this strategy, unnecessary investments are removed, and for the considered case study the results are:

- upgrade of the lines connecting buses 1-2, 2-3, 3-8, 7-8;
- power/energy upgrade of all existing storage units;
- investment costs equal to 2,792 k€.

Until now, step 2 disregards the inter-temporal constraints for the same reasons described in the previous subsection. However, in order to investigate the actual exploitability of

storage units for transmission/distribution services, their physical behaviour needs to be fully modelled (including energy capacity limitations, conversion efficiency, etc.). Therefore, having enabled the inter-temporal constraints and fixed the network investments to the ones listed above, a new OPF is carried out with the objective of minimizing the costs related to storage operation. This last run returns the baseline power profile for all the resources when step 2 candidates are selected.

As expected, the increment of investments reduces the necessity of local congestion management, leading to a different absorption/injection of active power for the upgraded storage units (Figure 6).

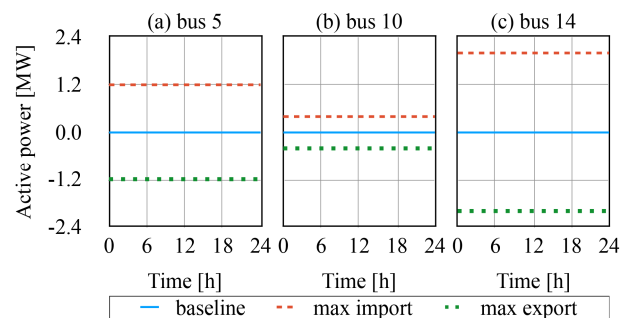


Figure 6. Storage units active power profiles returned by the step 2 of the proposed planning procedure.

The absence of temporary limitations demonstrates the full exploitability of the considered units for transmission network services. This means that, in case this planning option is selected, the transmission system would see a single equivalent storage unit, featuring 3.6 MW active power capability and 7.2 MWh storable energy.

3.3. Step 3 – Trade-off between minimum costs and maximum flexibility transfer from distribution to transmission network

Step 1 and step 2 represent two extreme cases in terms of distribution network planning, which lead to significantly different investment decisions and costs. Having considered the number of candidates, it is reasonable to assume that intermediate planning options are existing and their inclusion within the set of choices can increase their granularity (which is beneficial for the optimality of the final planning decision). Reasonable planning option could clearly involve investments which are more expensive than the ones returned by step 1, while cheaper than the ones of step 2. According to that, having selected an arbitrary budget for investments within this range of costs, the exact procedure proposed for step 2 is repeated (having added the budget constraint to the considered OPF problems).

For the case study, just one intermediate option (with investments budget set to 1,619 k€) has been processed and the selected investments consist of:

- upgrade of the line connecting buses 3-8 and 7-8;
- power/energy upgrade of the storage units connected to bus 5 and bus 14.

The evaluation of the amount of storage flexibility exploitable for transmission services can be computed as performed in step 2. In this case, the upgraded capability of the unit connected to bus 14 is fully exploitable. However, it is interesting to notice that the upgrade of the unit connected to bus 5 is not providing apparent benefits. This can be explained by observing that bus 5 is located in a congested area of the distribution network, and the local storage unit can be freely exploited for a limited amount of time. Therefore, this planning option would be seen by the transmission system as an equivalent storage unit, featuring 2.0 MW active power capability and 4.0 MWh storable energy.

Table 1 summarizes the main outcome of the entire distribution planning procedure and highlights the amount of equivalent storage flexibility that can be exploited for transmission services in the considered alternative cases. Of course, the higher the investments budget, the greater is the volume of the exploitable services.

Table 1. Overview of the planning options resulting from the analysis of the case study.

Planning option	Investment costs [k€]	Storage flexibility for transmission services
step 1	446	1.0 MW / 2.0 MWh
step 3	1,566	2.0 MW / 4.0 MWh
step 2	2,792	3.6 MW / 7.2 MWh

4. Conclusion

This work proposes a planning strategy for distribution networks, capable of exploring several planning options in terms of minimization of the operational/investment costs and maximization of local flexibility for the provision of services to the upstream transmission network. Although the procedure is characterized by a non-negligible complexity, its adoption introduces significant advantages for a global optimization of distribution and transmission systems:

- Automatic and independent distribution planning routine, which explores different options in terms of required regulation reserve for transmission services.
- Cooperation between system operators is expected to be simple and efficient, since the identified distribution planning options can be negotiated with a limited exchange of standard and non-sensitive information.

This approach, which is in its early development phases, has the main goal of supporting the decoupling of planning routines for transmission and distribution networks. This increases the computational tractability compared to solving a fully coupled joint optimization problem while still considering the interactions among different voltage levels.

5. Acknowledgements

The research leading to this publication received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 863819.

6. References

- [1] Silvestro, F., Pilo, F., Araneda, J.C., et al. 'Review of Transmission and Distribution Investment Decision Making Processes under increasing Energy Scenario Uncertainty'. 25th Int. Conf. and Exhibition on Electricity Distribution – CIRED, 2019
- [2] Schaefer, F., Menke, J., Marten, F., Braun, M., 'Time Series Based Power System Planning Including Storage Systems and Curtailment Strategies'. 25th Int. Conf. and Exhibition on Electricity Distribution – CIRED, 2019
- [3] Joint Working Group CIGRE/CIRED C1.29, 'Planning Criteria for Future Transmission Networks in the Presence of a Greater Variability of Power Exchange with Distribution Systems'. 2017
- [4] Pilo, F., Mauri, G., Bak-Jensen, B., Kampf, E., Taylor, J., Silvestro, F., 'Control and automation functions at the TSO and DSO interface – impact on network planning'. 24th Int. Conf. and Exhibition on Electricity Distribution – CIRED, 2017
- [5] Pilo, F., Mauri, G., Hanlon, S., et al., 'Control and automation systems for electricity distribution networks of the future – an update on the activities of joint working group CIGRE C6.25/ B5 /CIRED'. 23rd Int. Conf. and Exhibition on Electricity Distribution – CIRED, 2015
- [6] Kornrumpf, T., Zdrallek, M., Roch, M., et al., 'Flexibility Options for Medium Voltage Grid Planning'. 24th Int. Conf. and Exhibition on Electricity Distribution – CIRED, 2017
- [7] EPRI, 'Developing a Framework for Integrated Energy Network Planning (IEN-P)'. California, 2018.
- [8] Jendernalik, L., Giavarra, D., Engels, C., et al., 'A Holistic Network Planning Approach: Enhancement of the Grid Expansion using the Flexibility of Network participants'. 24th Int. Conf. and Exhibition on Electricity Distribution – CIRED, 2017
- [9] Migliavacca, G., Rossi, M., Siface, D., et al., 'The Innovative FlexPlan Grid-Planning Methodology: How Storage and Flexible Resources Could Help in De-Bottlenecking the European System'. Energies 2021, 14(4), 1194
- [10] Rossi, M., Migliavacca, G., Viganò, G., et al., 'TSO-DSO coordination to acquire services from distribution grids: Simulations, cost-benefit analysis and regulatory conclusions from the SmartNet project'. Electric Power Systems Research, Proceedings of the 21st Power Systems Computation Conference (PSCC 2020)
- [11] CIGRE Task Force C6.04, 'Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources'. 2014
- [12] Aigner, C., Witzmann, R., 'Effectivity of Active Voltage Control Concepts in Distribution Grids'. 25th Int. Conf. and Exhibition on Electricity Distribution – CIRED, 2019
- [13] H2020 EU project FlexPlan, 'Probabilistic optimization of T&D systems planning with high grid flexibility and its scalability'. 2021