FlexPlan

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

Flexibility elements analysis pre-processor simulation tool

D2.3

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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

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List of Abbreviations and Acronyms

Abbreviation/Acronym	Meaning
CAES	Compressed Air Energy Storage
DR	Demand Response
EV	Electric Vehicle
HVDC	High Voltage DC
LAES	Liquid Air Energy Storage
LM	Lagrange Multiplier
LMP	Locational Marginal Price
OPF	Optimal Power Flow
OS	Operative System
PST	Phase Shifting Transformer
PTDF	Power Transfer Distribution Factor
RCL	Regional Case Leader
RES	Renewable Energy Source
SW	Software
WP	Work Package

1 Introduction

This document presents the methodology considered as a reference for the development of the flexibility candidates selection pre-processor tool of the FlexPlan project, as well as a short manual illustrating the settings that are considered within the software, so that they are clearly identified and can be adjusted, if necessary, in the different phases of the development.

The document analyses also the integration between the pre-processor and the planning tool to achieve an automated and complete network planning methodology within the FlexPlan project.

2 Flexibility analysis methodology and software

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, 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.
- Subsequently, a "corridor analysis" is carried out to avoid that expanding the lines located with the procedure of the previous bullet just shifts congestion to some other line of the network. This analysis is done by considering the so called Power Transfer Distribution Factors (PTDF), which provide a linearized description of active power flows in the network.
- The flexibility resources analysis tool (pre-processor) proposes a list of network expansion candidates, including storage, demand response (DR), phase-shifting transformers (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 two main tasks that are carried out by the pre-processor to perform the flexibility resources candidate's preselection are the following:

1. Selection of congestion scenarios.
2. Selection of candidates.

The following Figure 2.1 graphically summarises the steps carried out by the pre-processor in relation with the planning tool.

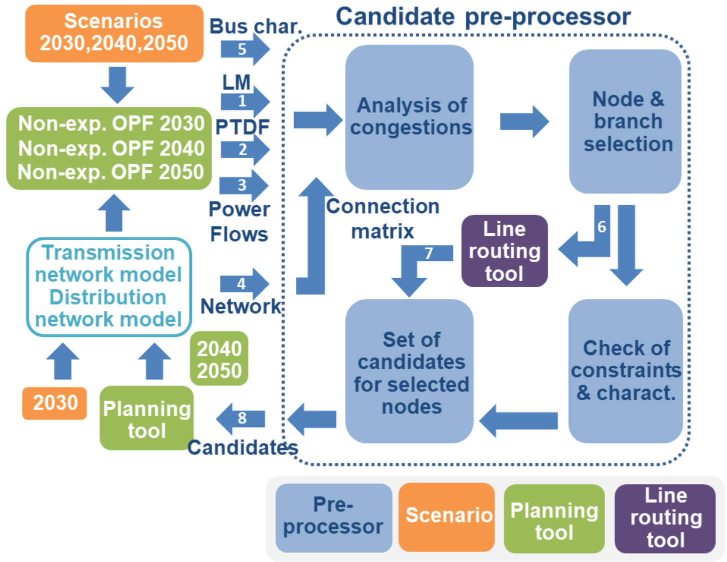

Figure 2.1 – Pre-processor tasks in relation to FlexPlan planning methodology

As starting point, an OPF of the non-expanded network is carried out by the OPF module included in the planning tool software suite. As a result of this, Lagrange Multipliers (LM), Locational Marginal Prices (LMP) and Power Transfer Distribution Factors (PTDF) values are provided to the candidates' pre-processor. In addition to this, the pre-processor also takes as input the network model and the bus characterization performed by the user and included in the grid model data format. With these inputs, the main steps of pre-processor are carried out: first, the analysis of congestions and the selection of the nodes and branches that need to be upgraded; second, the check of location constraints and congestion characteristics; third, the pre-selection of a set of candidate technologies, including cost and size. In this last case, an additional tool, the line routing tool (described in D1.2, par.6.3), is used to provide line candidates between to nodes or substations. Pre-selected candidate technologies are handed over to the planning tool, which performs the optimization and selects among them, those that provide, altogether, a best network expansion solution. This is performed in loop, for the three time frames 2030, 2030-2040, 2030-2040-2050.

The following Table 2-1 lists the identified interfaces between the pre-processor and the other project tasks following the numbering Figure 2.1.

Interface	Description of required info.	Who	Format
1	LMPs (Locational Marginal Prices) & LM (Lagrange Multipliers)	Planning tool	JSON
2	Power flows in branches resulting from the OPF	Planning tool	JSON
3	Power Transfer Distribution Factors (PTDF)	Planning tool	JSON
4	Non-expanded network model	User/Planning tool	JSON
5	Bus characteristics and constraints	User	JSON
6	From and to nodes & power rating of candidate branches	Pre-processor	JSON

7	Technical characteristics and cost of candidate lines	WP1 tool	JSON
8	Set of candidates for selected nodes	Pre-processor	JSON

Table 2-1 - Flexibility resource mapping to the congestion characteristics

2.1 Selection of congestion scenarios

A yearly congestion analysis of is carried out and, from it, a selection of the congestion scenarios is done.

2.1.1 Required inputs for the selection of congested scenarios

There are two main inputs to perform the selection of congested scenarios:

- **Optimal Power Flow (OPF).**
- **Transmission and distribution networks models and scenarios.**

The non-expanded OPF module run within the planning tool suite first performs an OPF for the non-expanded network:

- for the year 2030,
- for 2040 (including a trial expansion in 2030)
- for 2050 (including a trial expansion in 2030 and 2040)[1].

Four types of inputs are provided by the planning tool at this stage: The Locational Marginal Prices (LMPs), the Lagrange Multipliers (LM), Power Transfer Distribution Factors (PTDF) and the power flows in the branches of the system.

Lagrange Multipliers of lines transit constraints (LM) are a direct outcome of the solution of the optimization problem (OPF). They provide information about the dispatching cost reduction deriving from 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 value and such value will correspond to the dispatching cost reduction deriving from a 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. They provide useful information for the location of flexible resources (storage and DR).

We could say that the LMs represent the value of the interconnection capacity of the corresponding line and the LMPs the value of energy in the corresponding node. More details on these two concepts are available in [1].

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.

In a year-long simulation, the OPF provides a value for all these three parameters for each of the 8760 hours and for each of the buses and branches.

[1] Each time the planning tool calculates a full set of expansions for the three years: 2030, 2040 and 2050

The **Power Transfer Distribution Factors** (PTDF) matrix represents the change in the active power flow through a network branch as a consequence of a unit extra injection in a given system node. This information is dependent on the topology and, therefore, it is considered constant for one year of study.

The **topology of the network** provides the relationship between buses and branches and the characteristics of network elements (the power rating of the branches, electrical characteristics of network assets…). The overall network model includes transmission, sub-transmission and distribution networks models.

A data format, based on JSON files[2], has been created within the project to define the grid model and generation and load scenarios. The non-expanded networks for 2030 (including transmission, sub-transmission and distribution) are defined by the users of the tool in this format, as input for the planning tool. In the frame of the project, the Regional Case Leaders, i.e. the leaders of each of the 6 regional studies targeted by FlexPlan, are in charge of this task.

2.1.2 Tasks for the selection of congested scenarios

The **processes** that are carried out by the pre-processor to identify the congestion scenarios are the following:

1. All the system **branches' LM values are checked**. The LM value evolution along the year is analysed statistically, but two main values are considered:
    a. Number of hours in a year, when the LM value is different from zero.
    b. Average LM value considering all year hours (sum of LM values for a branch, along the year).
2. Based on the previous statistical results, a number of lines is selected, reflecting the **most congested lines** in the system. It is also checked that the number of total congestion hours in the year is higher than a minimum (it could be zero) to avoid choosing very punctual congestions. To take both aspects into account, the following factor is used: the **yearly average LM times the occurrence**. In this process, forced candidates are assessed first. Forced candidates are those proposed by the user: a pair of nodes that are selected directly upon request as candidate location for building new lines.
3. For the selected congested lines, the **power flow direction** along the year is studied to check whether the congestions occur in one or two directions.
4. The **hour of the year with highest congestion** (highest LM) is identified for each selected line. All the identified hours represent the selected **congestion scenarios**.

This congestion scenarios' selection process is automatically launched, when the non-expanded OPF results are available from the planning tool after a simulation.

[2] A JSON file is a file that stores simple data structures and objects in JavaScript Object Notation (JSON) format, which is a standard data interchange format. It is primarily used for transmitting data between a web application and a server. JSON files are lightweight, text-based, human-readable, and can be edited using a text editor [2].

The following **Errore. L'origine riferimento non è stata trovata.** shows the steps performed by the pre-processor tool for the selection of congested scenarios (l: line; cg: congested; cgcons: consecutive congestions; cgerr: congestions not relieved).

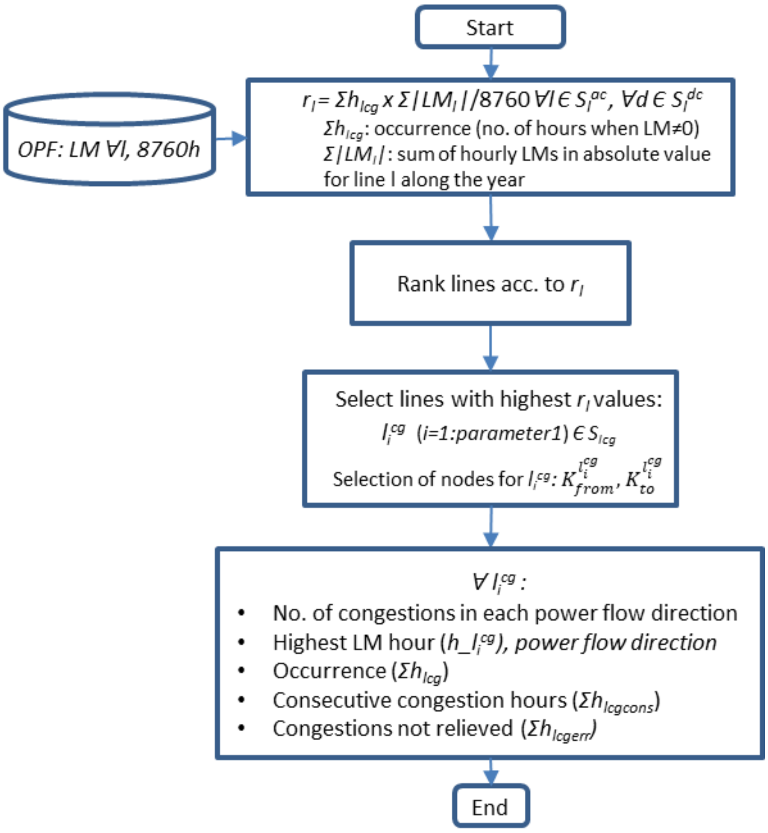

Figure 2.2 – Flow chart for the selection of congestion scenarios

2.2 Selection of candidates

The selection of candidates is mainly linked to the relief of the congestion constraints. Therefore, a set of candidates is proposed for each of the congestion scenarios identified at the previous step, which are related to a specific location in the network.

The flexibility candidates considered by the tool are the following:

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

All the technologies above are considered as possible candidates for network extension. However, 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. The selection of candidates at a specific node or branch is screened according to this characterization: the network information provided for nodes is used to discard, or not, some of the candidate technologies.

In order to process these characteristics automatically, a heuristic approach is assumed to check the constraints and network characteristics at different levels:

- **Location constraints:** the grid model allows the characterization of network nodes to include existing constraints. These are the characteristics that can be assigned to each network node or bus (underlined are the ones used in the current version of the tool):
    - **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, if no hydro power plant is present); 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, indicate main type/s).
    - **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 hydro plants; for hydrogen; for batteries; for CAES/LAES; total restriction.
    - **Is interconnection:** if certain bus is connected to a bus in another country/region, it is considered suitable to install a PST.
- **Existence of industrial load at a selected node:** it allows to propose DR candidates among the large loads in the system.
- **Congestion characteristics:** the characteristics of the congestion, such as the number of congestion hours in one year or the number of consecutive congestion hours, make some candidate technologies more appropriate than others to solve them: e.g., if congestion tends to last more than six hours, batteries or demand response strategies might not be the best flexibility candidates. These rules are also implemented in the pre-processor tool.

Once the most suitable technologies have been selected for a location, the pre-processor provides a size and cost for each of them. In the case of the lines, an external software for line routing between two nodes is used to identify the characteristics and cost of both AC and DC candidate lines.

A second path for candidate pre-selection is through the direct proposal candidates by the user of the planning tool (in the frame of the project these would be Regional Case Leaders). The users need to provide a *from* and *to* nodes, indicating the branch they would like to assess from the congestion point of view in the system. At this moment, this is used for nodes that do not have a direct connection in the non-expanded grid model and that the user would like to consider as candidate options, since the candidates' pre-processor does not take into account this casuistry (no LM information would be available from the OPF).

The technologies are analysed in a predefined order (first storage) and when the limit of candidates is reached, no more candidates are included in the candidate list.

The analyses performed for every selected congested line and for each technology type are carried out for the **congestion scenarios.** The following flow chart shows the general steps for the selection of candidates.

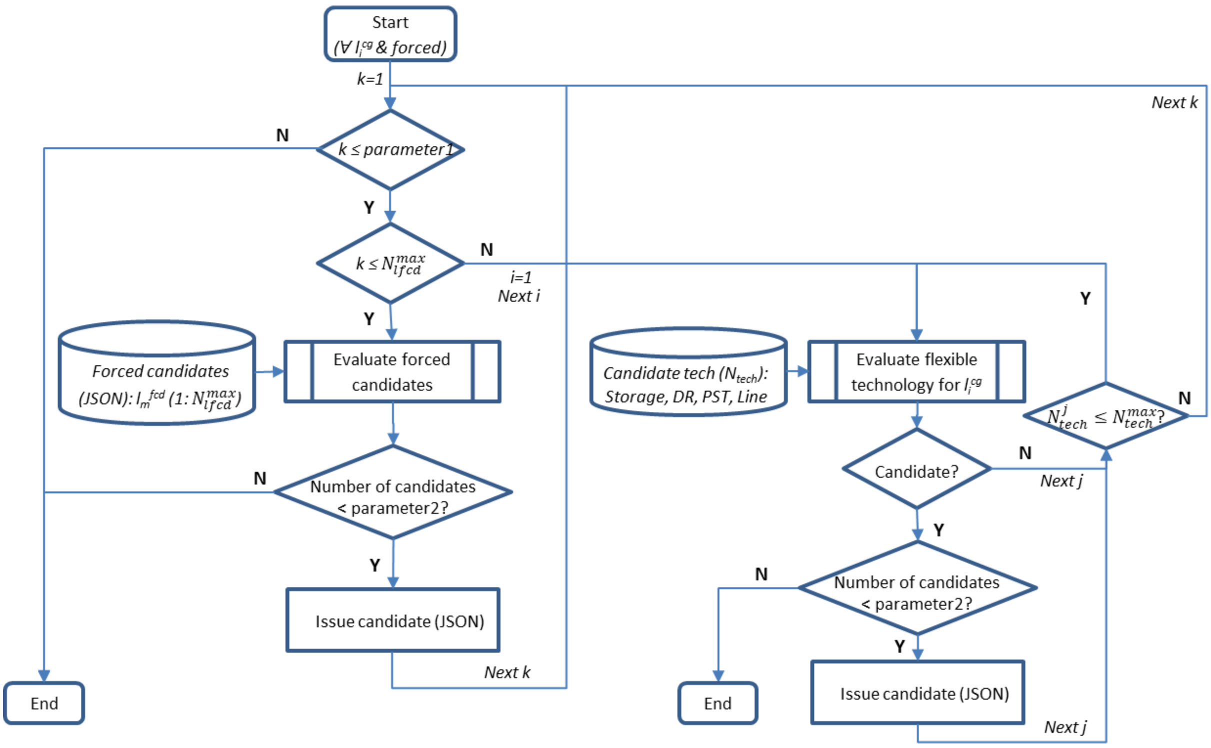

Figure 2.3 – Flow chart for the selection of candidates (general)

In the following sections, the specificities of the methodology related to each flexibility technology are reviewed.

2.2.1 Storage

Starting from a selected congested scenario, the following steps are carried out to define the storage candidates to solve that congestion:

1. From the selected congested line/s, the **most suitable node** to solve the congestion is selected. The node with the highest LMP is the preferable, which is a result from the OPF and indicates the cost to service the next increment of demand (1MW). In this case, it is also checked that the power flow in the congestion scenario is coherent with the power flow direction in the majority of congested hours along the year for this line:
    - If one of the nodes has higher LMPs in the majority of the hours (e.g. 75%) when the line is congested along the year, that node is selected as preferred location for the storage.
    - If the power flow in a line during congested hours does not clearly show a preferred direction (e.g. 75% towards one of the end nodes), then storage is not considered a good candidate for this location.
2. **Locational restrictions** are checked for each selected node (a table is provided in Annex I which provides an example of how to indicate these restrictions). If:

   a. Restrictions exist: we do not select the location as candidate.
   b. No restrictions exist: we select this location.
3. **Congestions characteristics** are checked to eliminate not suitable storage technologies (Annex I):
   a. The yearly number of congestions in the table is measured considering the number of hours in the year when the value is different to zero.
   b. The number of consecutive congestion hours is valued considering its percentile 75, excluding zero values (in order not so oversize the storage by considering the maximum number of hours as reference).
   c. In addition to Table 6-1, if the percentage of congestion hours not relieved (e.g. hours when the storage is not able to solve a congestion because it is empty) is lower than 20%, batteries are not an option.
4. One or more **sizes and related costs** are proposed for the selected technology type (Annex II, providing "standard sizes and cost for flexible resources"). The size is proposed in relation to the rated capacity of the congested line. The energy content (size of the storage in energy) of batteries is calculated in relation to the number of consecutive congestion hours. The size of the hydrogen and pumped hydro storage is defined as a percentage of the annual number of congestion hours (e.g. 50%), as nominal power per annual hours. For CAES and LAES we consider, in principle, that the storage is able to store energy in the 100% of congestion hours.
5. In the case that **two or more congested lines meet at a node**, two options are considered (when no restrictions are present):
   a. If the lines come from the same node (parallel lines): a resulting storage will be proposed for the *to* bus of the congested branch, consisting in a power equal to the sum of all storage powers calculated for each of the congested lines and the capacity (energy) equal to the maximum capacity (in hours) among all calculated storages (in accordance to the previous point).
   b. If the lines come from different nodes: independent storages are proposed at the node, one per congested branch, so that the planning tool can consider them as independent network expansion options.

Previous steps are shown in a chart in the next Figure 2.4.

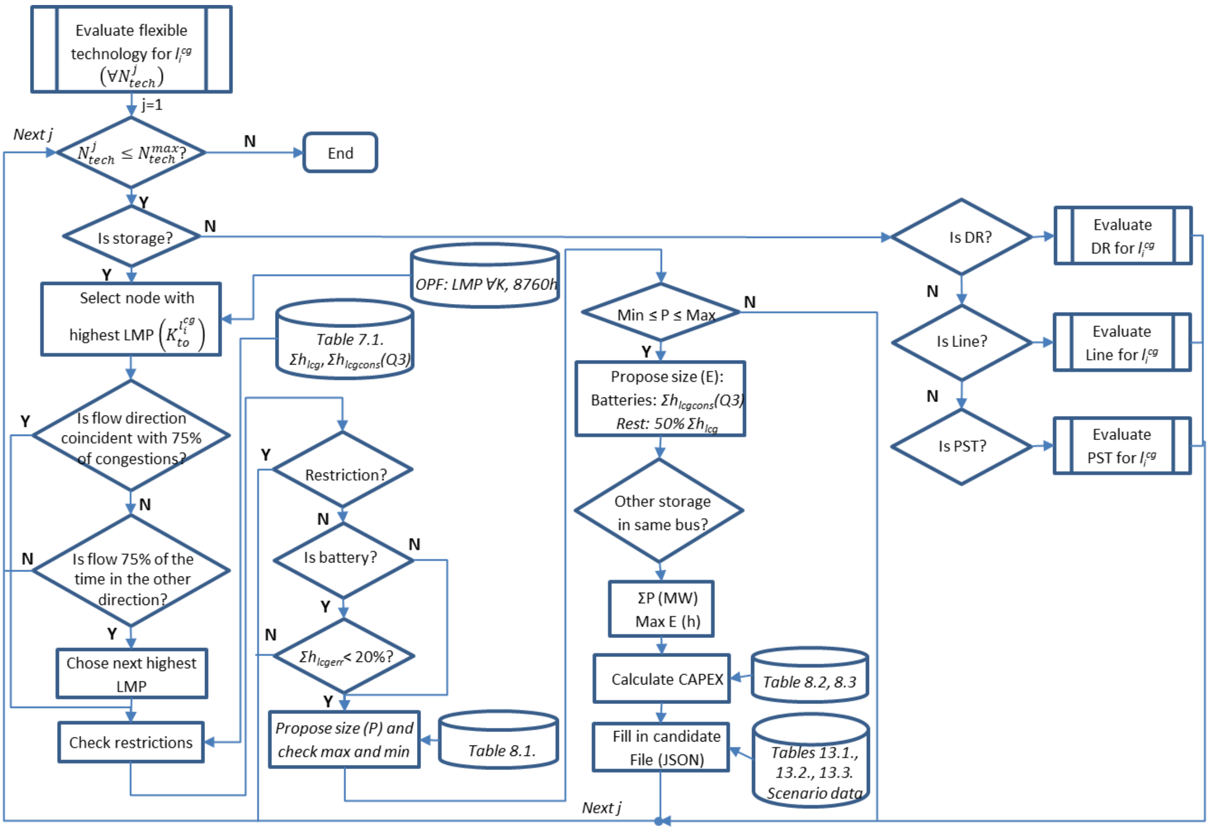

Figure 2.4 – Flow chart for the selection of candidates (flexibility and storage)

2.2.2 Demand Response (DR)

Starting from a selected congestion scenario, the following steps are carried out to select flexible loads able to provide Demand Response actions to solve that congestion:

1. From the selected congested line/s, select the **most suitable node** to solve the congestion. In the case of demand, the node with highest LMP is selected among the two of the congested line. When the congestion flow in a branch changes direction along the year, both nodes from a branch are selected (e.g. when both have higher LMP values more than 25% of the congested hours). DR does not imply to build a new installation so, if a flexible load exist, both nodes of a congested branch are selected as candidate.
2. **Locational information** is checked for each of the selected nodes (Annex I), if:
    a. If no flexible load is available, the node is not selected.
    b. If a flexible load is available at that bus and the characteristics of the congestion do not prevent the use of DR, DR is selected as candidate for the node.

    Since building new "loads" is out of the scope, no locational restrictions are considered.
3. A "**maximum size/flexibility**" and a **cost** are proposed for the selected load type in accordance to Table 7-4, which is an input that can be modified. It is assumed that DR refers to load shifting[3],

[3] Load reduction is normally related to modification in processes or consumption equipment, which leads to a persistent reduction in consumption, while obtaining the same service. In the residential sector,

especially in the industrial sector (it happens that some reduction may exist but that would mean that the process it is not optimized, which might be realistic, but probably not to be assumed here). Load shifting is downwards in the congestion hours. The way this consumption is "recovered" (where it is shifted) is something that depends on the process affected by the reduction e.g., if it is a process that permits storage of goods, the downward load could be shared among hours before and after the congestion; if it is a high consumption process, the same reduction would represent an increase in another hour when no congestion exists. It is difficult to say which is the reality for the studied cases, so a default approach is used.

The following Figure 2.5 represents the algorithm performed by the pre-processor to select a DR candidate.

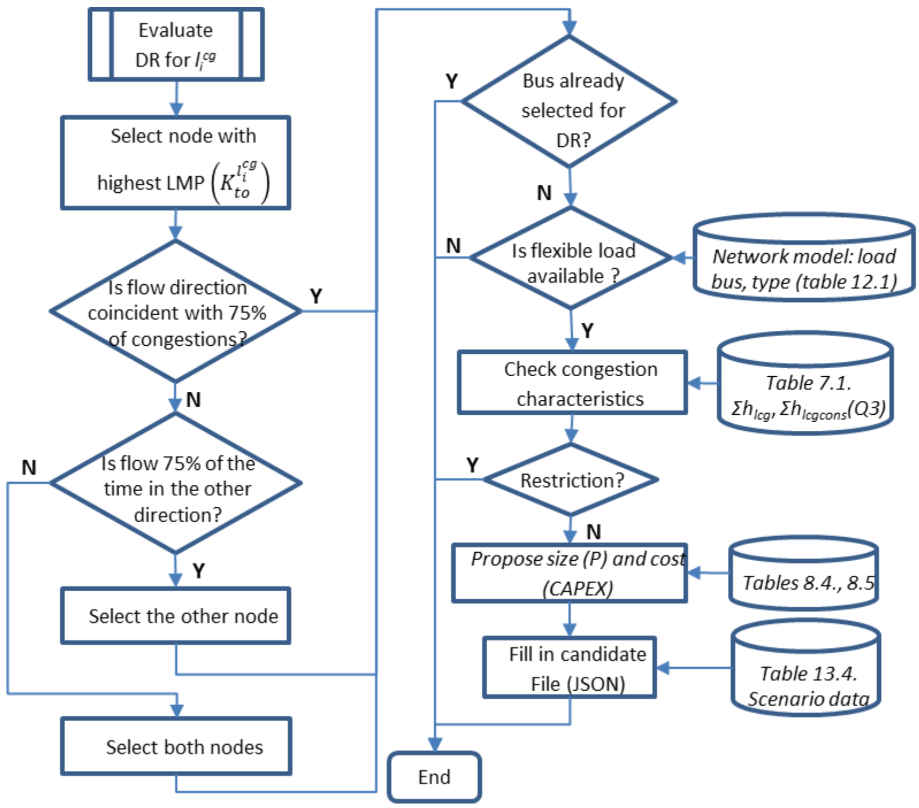

Figure 2.5 – Flow chart for the selection of candidates (DR/Flexible loads)

2.2.3 Line

Two different approaches are considered here to select lines for network expansion, depending on the previous existence or not of lines.

Steps for existing lines:

If a congestion is identified on an existing line in the network (selection of congestion scenario), the following steps are carried out:

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a service reduction (comfort, for example) can be permitted, but in industrial and commercial sectors demand is optimized due to the direct impact on costs. Load curtailment is not considered as DR, but as an emergency action by the system operator.

1. The *from* and *to* **nodes** of the congested branches are selected.
2. **Locational restrictions** are checked (Annex I).
3. For all the lines in the systems, the **saturation** percentage, $\alpha_{L,LC}$, is calculated based on equation (7) in Annex III, which provides a methodology to avoid, in meshed networks, that solving the congestion in one branch may cause that others become congested in its surroundings. For this purpose, the Power Transfer Distribution Factor (PTDF) matrix is used, which is provided by the planning tool as result from the OPF:

$$\alpha_{l,lc_{[s,s]}} = \frac{PTDF_{K_1-K_2}(l_c,1)}{P_{lc}^{max}} M_{[s,s]}^{-1} \left(P_l^{max}{}_{[s,s]} - P_l^0{}_{[s,s]}\right) \quad (1)$$

Where:

- $PTDF_{k1\text{-}k2}$, is a one column matrix resulting from subtracting the two columns related to nodes k_1 and k_2 of the PTDF matrix.
- S, is the number of non-zero elements in the column $PTDF_{k1\text{-}k2}$.
- $PTDF_{K_1-K_2}(l_c,1)$ is the element $(lc,1)$ in $PTDF_{k1\text{-}k2}$.
- M is a diagonal matrix formed with the non-zero elements of $PTDF_{k1\text{-}k2}$.
- P_l^{max} is a diagonal matrix formed with the rated power of the lines included in M matrix (those with $PTDF_{k1\text{-}k2}$ elements equal to zero are discarded).
- P_l^0 is a diagonal matrix formed with the DC power flow values of the lines included in the M matrix.

4. Lines with a value of $\alpha_{Ls,LC}$ lower than a limit are considered as candidates, together with the congested line. Their *from* and *to* nodes are selected. A maximum number of **candidates derived from the influence of a congested line** is permitted.
5. If a line is **selected twice**, because it is congested and because it is influenced by another congestion, only one candidate is provided (no repetition).
6. For each of these selected lines, we propose a line of the **same rating** as that of the congested one. We are following the approach of adding a new line between the nodes of the congested lines (it is to be checked the possibility of considering dismantling the old and placing a new line). Some of the identified branches could be also transformers. In that case, a transformer will be proposed as candidate, in principle, with the same characteristics as those of the existing one. If more than one parallel line exists between two nodes, only one additional line is proposed as candidate with the rating of that of highest power among them (not the sum of the rating of all existing lines).
7. The information related to lines, nodes (substation) and power rate, is provided to the **line routing software[4],** which selects the best routing and cost for both an AC and a DC connection option. A JSON candidate file (input for the planning tool) is used for the exchange between both tools of WP2 and WP1: regarding line candidates, some fields are filled in by the flexibility candidate pre-processor and others by the line routing tool. If there is no available location

[4] The line routing software (see deliverable D1.2, par.6.3) is a tool used in WP1, which for a given pair of substations and a power transmission level, provides an optimum solution for line routing and technology selection.

(geographic coordinates) for nodes, the line routing software cannot be used so a line equal to the existing one is proposed at the cost defined from existing default data (literature based).

8. Once the missing fields of lines are completed by the WP1 tool, the **candidate input file** is handled over to the planning tool, including all candidates of any type.

The steps to select line candidates are represented in the next flow chart (Figure 2.6). It is valid for AC line, DC line and transformer technologies.

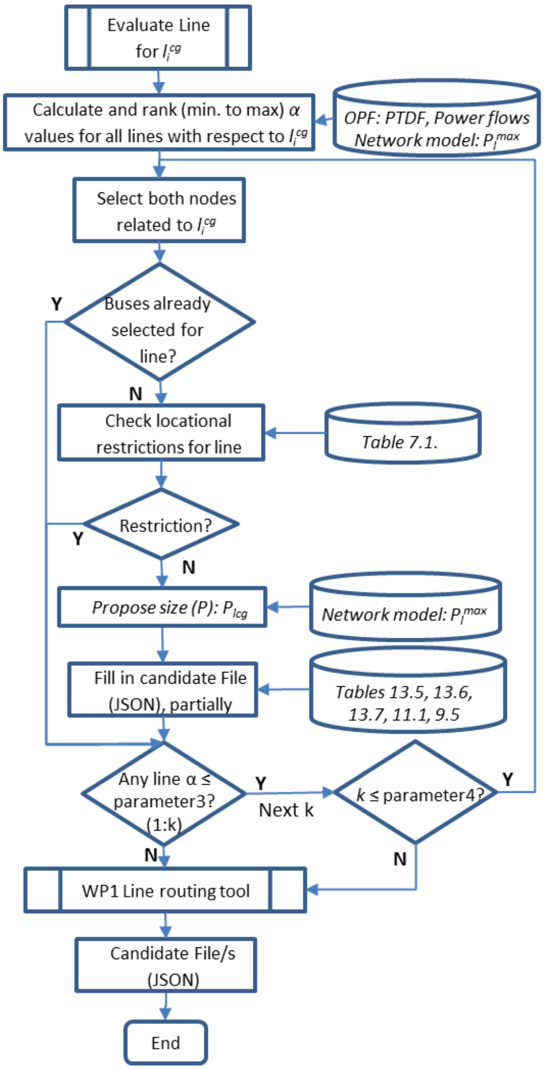

Figure 2.6 – Flow chart for the selection of candidates (AC and DC lines and transformers)

Steps for non-existing lines:

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 and included as first choices in the candidate selection process. In this case:

1. The **candidates should be proposed** by the planning tool users (Regional Case Leaders in the frame of the project) externally through the identification of: *from* and *to* nodes, including geographical location, voltage level and power. The defined candidate file formats in JSON are used.
2. These information, nodes (substation) and power rate, is provided to the **line routing tool**, which selects the best routing, technology (AC and DC), and cost for the technology. The candidate files for the planning tool are used for the exchange between both tools: some fields are filled in by the pre-processor and others by the line routing tool. The pre-processor pre-fills in templates for both AC and DC lines/converters and the line routing tool completes the information to present both technologies as candidate for the planning tool to decide.
3. Once the information related to line candidates is complete , the **candidate input file** is handled over to the planning tool.

The following flow chart represents graphically the steps above.

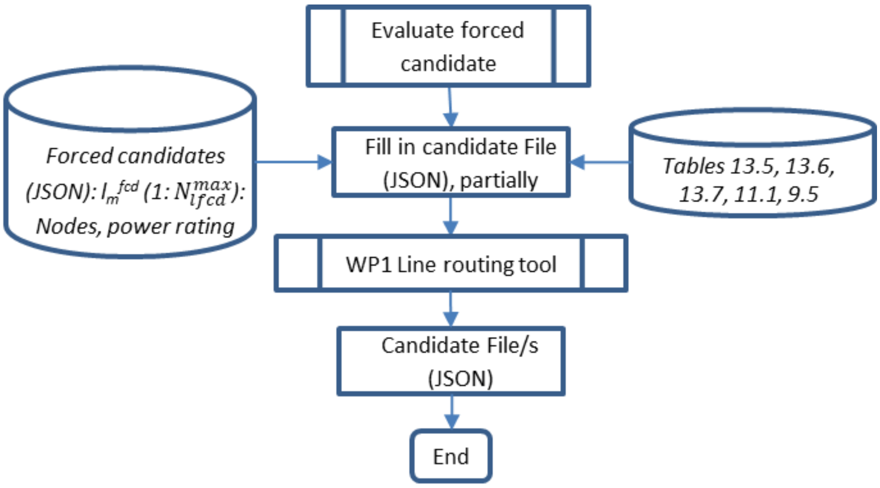

Figure 2.7 – Flow chart for the selection of candidates (forced AC and DC line candidates)

2.2.4 PST

The PST changes the reactance of a line and, therefore, the voltage angle difference between its both nodes. As consequence, also the flows in other branches are modified. In principle, as first rule of thumb, all **interconnection lines** between countries that are congested are considered as candidates.

Steps:

1. Check if the congested line is an interconnection between two countries (locational constraint information).
2. Locational restrictions are checked (Annex I), if:
   a. The conditions to install a PST are not met: no PST option is selected.
   b. The conditions to install a PST are met: we select PSTs as candidate for this location.
3. The rating of the PST is linked to that of the branch. Related costs are taken from standard values (Annex V, which provides PST related data). The characteristics of the PST should be similar to those of a Transformer of the same rating. From the percentage impedance (u_x) in Table 10-2, reactance is calculated as:

$$X = \frac{U^2}{S} u_x \quad (2)$$

The flow chart for the PST candidates' selection is the next Figure 2.8.

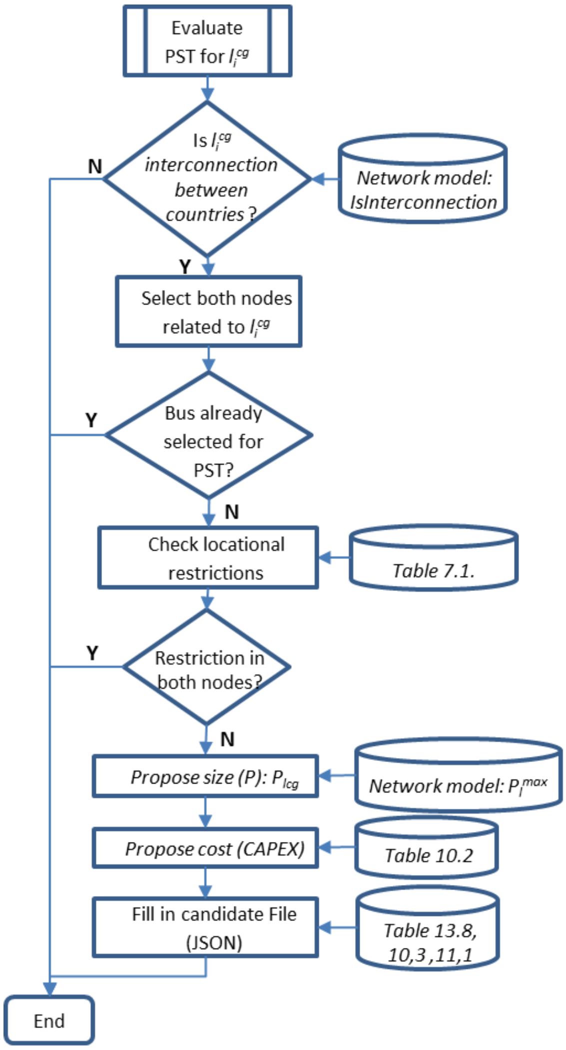

Figure 2.8 – Flow chart for the selection of candidates (PST)

2.3 Outputs from the pre-processor

The outputs from the process of the selection of candidates are handled over to the FlexPlan planning tool. According to the methodology, this below is a summary of the most relevant information provided by the flexibility candidates' tool to the planning tool:

- A **location** in the network (bus/branch id.) for the flexibility resource.
- A **list of candidate flexibility resources** for each location is selected among the following: storage, flexible loads (leading to DR strategies through existing load shifting or/and reduction), Phase Shifting Transformer (PST) and line (AC, both overhead and cable, HVDC).
- A **size** for each candidate: an approximate size for each technology is provided. In the case of flexible loads, a load reduction percentage capability is indicated. This reduction is by default related to a shift of load, in the industrial and commercial sectors, which means that this reduction will have to be compensated in the next hours to be able to provide the same service.
- A **cost** for each candidate: CAPEX or CAPEX and OPEX per power is provided (operation and maintenance costs, not related to the fuel or dispatching costs), depending on the type of technology (according to its definition in the optimization problem, WP1). The information comes from [3].

2.4 Integration with the planning tool methodology

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 (this is currently done by a module of the planning tool suite), 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).

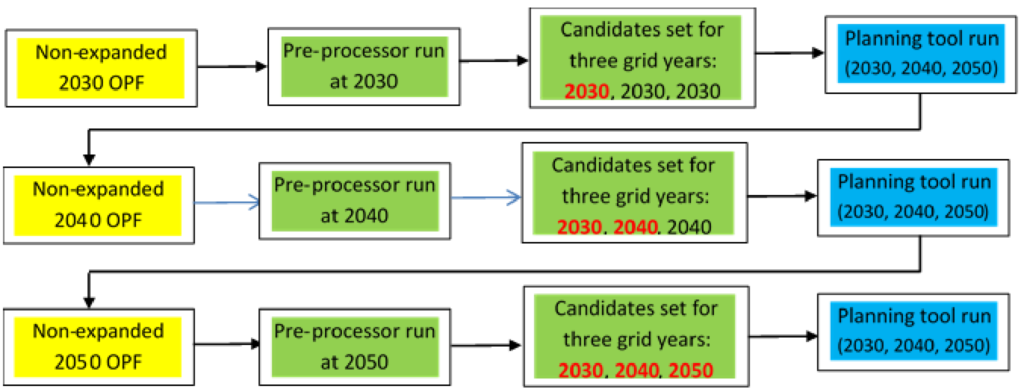

Figure 2.9 – Interaction between planning tool and pre-processor.

After all line candidates for grid expansion are selected, the pre-processor interacts with the line routing software tool (see footnote 4 on page 18), 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.

According to the planning tool architecture, the interaction with the client, i.e. the user of the tool (e.g. Regional Case Leaders), and the pre-processor is summarized in the following Figure 2.10. The figure also shows the link between the pre-processor and the **line routing tool**, which provides the line characteristics between two substations.

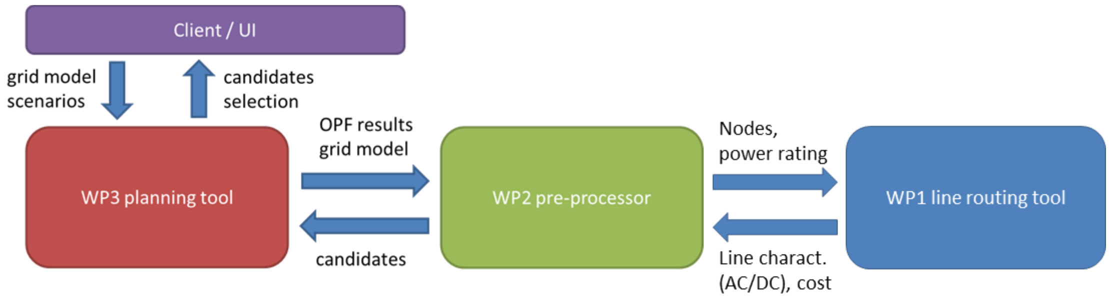

Figure 2.10 – Interaction between planning tool, client and pre-processor

3 Short manual of the pre-processor tool

The present chapter focuses on the settings that need to be defined in the pre-processor tool to obtain the expected results from the network planning process, in accordance to the previously described methodology.

Some values have been adopted and are proposed for the settings, however they are subject to change if more accurate ones are found or the results that are obtained from the planning process show that other might be more appropriate.

3.1 Main settings for the pre-processor

There are different settings that the user needs to define for the pre-processor to provide the required outputs. The quality of this inputs impacts the quality of the planning process, so there need to be as actual and specific to the region under study as possible.

The main settings that need to be defined are the following:

- Locational and congestion constraints.
- Flexibility candidates' cost and size.
- Other parameters related to flexibility candidates.

At the moment, some of the required information is introduced at grid or scenario model level (through the JSON format files used for the planning tool) and other data is introduced at coding level, starting from standard tables in text format that can be easily filled in by the users of the tool.

3.1.1 Locational and congestion constraints

The pre-processor checks if a location, selected because congestion exists, is appropriate for a certain flexibility resource.

To do this, the first step is to introduce information about the location. To characterise the location, a list of codes is available for buses description in Annex VII (Table 12-1), in line with the information described in the introduction of section 2.2. This information is introduced in the Grid Model Input File of the planning tool: in the part related to both *AC and DC buses* and, inside here, in the sub-part related to *characteristics*.

Since doing this for every network node might not be an easy task, it is recommended that this information is provided after a first analysis of the network has been performed, i.e., after congestion points have already been identified and congestion scenarios selected. This would allow to provide this additional information only for the nodes that might be affected by a congestion.

If no information is provided no restriction is considered, but there is one exception to this general rule, the resource availability data, if it is not specified that there is water available or that there are caverns available, hydro power and CAES are not considered as candidate by the tool.

After the characterisation of the nodes has been performed, the rules affecting the constraints need to be defined. Table 6-1 shows an example of the information that should be provided:

- **Type of bus**: if the type of bus is an air substation no restrictions are considered (in the example, only underground cables have been considered as not suitable); if the substation is underground, those technologies that require a significative space have been restricted (e.g. batteries and PST). If the substation is a generator or a load, the installation of storage solutions is something to be decided by the owners of the plant, so it is not considered a suitable location to install storage by the system operator. In the case of loads, they are eligible as demand response candidates.
- **Resources**: the absence of water prevents the use of hydro power as solution and the absence of caverns the use of CAES systems, in the example. No other resources set a restriction.
- **Location**: the location of the bus, implies other restrictions. Urban areas do not allow the installation of voluminous or wide area systems on the ground. Rural areas do not have restrictions related to the required space, but if the area is mountainous some of the technologies are less suitable because of the problems or costs to install them.
- **Restriction:** this is the way to indicate that a certain technology or that all technologies, whatever the reasons, are restricted at a certain bus.
- **Constraints related to the congestion characteristics:** the number of consecutive hours of congestions may prevent some technologies to be adequate to solve them. For example, if congestions last more than six hours, batteries and demand response do not seem good flexibility options. Also, the total number of congestion hours in a year is a parameter considered for this purpose. For example, batteries require the same discharge and charge time, so if a congestion appears at a certain location more than half of the hours of the year, that would mean that the battery would be empty in many occasions during the year, unable to solve congestions.

3.1.2 Flexibility candidates cost and size

The pre-processor needs to provide a size and cost for each selected flexible technology at a location.

In the optimization process by the planning tool, the size of candidates is not optimized, therefore, the pre-processor needs to provide an estimated size. The planning tool can deal with different sizes for each technology, selecting the optimum among them, but this means increasing the number of candidates and, therefore, the size of the problem.

Most of the information described in this section is included within the pre-processor coding (except when specified).

Different approaches are considered to define the **size** of the candidate depending on the technology:

- **Storage**: the power rating of the storage candidate is considered as a percentage of the congested branch power rating (Table 7-1). It is considered that if the system is well designed, the congestion should not be well above the rated power of the lines (thinking of an unconstrained power flow problem) and that, as result, this percentage should be relatively small. Maximum and minimum sizes of the storage are defined for each technology, so if the power rating calculated does not fall within that range, this technology is not considered candidate. The energy rating of batteries is calculated in relation to the amount of consecutive congestion hours; that of the pumped and hydro plants is considered to be half of the congestion hours in a year; and the related to CAES and LAES to 100% of the congestion hours in a year.

- **Lines and transformers**: the proposed line and transformer candidates' power ratings are equal to those of the congested line or transformer. It is considered that, if the power needs to be increased, a line or transformer similar to the existing one will be installed (as general rule). If a new line is proposed where a line did not exist previously, the user should provide the power rating of the new line.
- **Flexible loads (or demand response)**: for some selected big commercial and industrial loads, a typical load reduction capability has been identified (Table 7-4). Even if the reference values of this demand reduction were originally expressed in absolute values, they need to be translated to percentages because of the format required in the input JSON files. For those big industrial and commercial loads not defined through an activity, a 50kW value has been adopted as demand reduction potential. This is a value required at the *Scenario Data Input File – loads - flexible load scenario* field.

In principle, technologies which are more scalable in size, as batteries, could permit to play with a higher degree of sensibility in the optimization phase, permitting a better sizing of resources at global level.

Regarding the **cost**, some standard values need to be introduced by coding to the SW tool. The investment cost (CAPEX) is an input required by the planning tool through the JSON formats:

- In the case of batteries, the costs depend on both the installed power (cost per kW) and on the energy capacity (cost per kWh) (Annex II, Table 7-2).
- In the case of other storage, the cost is per installed power (Annex II, Table 7-3).
- In the case of demand response and flexible loads, the cost is per power reduction (Annex II, Table 7-4).
- In the case of lines, this information is provided by the line routing tool, however, this tool cannot provide results if the information on the geographical location of *from* and *to* nodes is missing. For this last case, a standard cost is provided per rated power of the line (Annex IV, Table 9-1., this annex provides line and transformer related information), including converters when the line is HVDC (Annex IV, Table 9-3). This last approach is also used for transformers (Annex IV, Table 9-2).
- In the case of PSTs, the cost is per rated power (Annex V, Table 10-1).

3.1.3 Other parameters related to flexibility candidates

Location, technology, size and cost are the main outputs of the pre-processor for the planning tool. However, technologies should be characterized more extensively in accordance to the data models required by the planning tool, defined in JSON format.

These data models, which are currently not yet at their definitive version, are represented in the tables of Annex VIII (section 13), at least for all obligatory fields (certain fields of the model are optional).

The information included in these tables comes from different sources:

- Literature, including previous deliverables from FlexPlan project (mainly [3]).
- Pre-processor calculations.
- Line routing tool calculations.
- Grid model or scenario definition.

- Assumptions based on common practices.

3.2 Software installation and output folders

The planning tool interacts directly and in an automated way with the pre-processor. It is hosted in a web server (cloud) and it is accessible through a web API. JSON format files are used to exchange the information between them, in accordance to the planning tool specifications.

The pre-processor is developed in a separated environment, but it is hosted in the planning tool server as a docker image, to achieve an adequate integration between both tools.

The flexibility candidate pre-processor also interacts with the **line routing tool** that optimizes the routing of a line between two substations. The same approach as that used for the planning tool is developed:

- Docker images are used: one image for the planning tool, one for the line routing tool and one for the pre-processor.
- Candidate files in JSON are used to exchange inputs and outputs between both tools.
- These tools are integrated and the interaction with the planning tool is led by the flexibility candidate pre-processor, which provides a candidate list including the outputs lien routing tool.
- The process automation follows the same philosophy as that between the pre-processor and the planning tool.

An OS folder, mapped within the image containing the application, is used to share output and input files between the pre-processor and the other two tools. The following-folder tree is used by the pre-processor, in principle:

- **Scenario No.**:
  - **Input**: including input files for the pre-processor coming from the planning tool: grid model, scenario data input file, candidate files (only “forced” candidates defined by users), OPF results (LM, LMPs, power flows and PTDF matrices).
  - **Output:** including output files from the pre-processor to the planning tool and to the WP1 line routing tool. Three files will be hosted here:
    - CandidatesInputFile_WP2.json: output from pre-processor, input for line routing tool.
    - CandidatesInputFile.json: input for planning tool (candidates), some of them (line candidates) output from the line routing tool.
    - Log file: text file including a summary of results, e.g. the number of candidates per branch (e.g. here, we could see if a location has no candidate).
- **Debug scenario**: including files that provide additional information for debugging purposes, such as error log, congestion maps, output text files…

3.3 Debugging

Apart from the selection and sharing of the candidate technologies by the flexibility pre-processor software, which needs to be transparent for the software user and needs to permit an automated operation, some other outputs are provided by the tool to allow debugging or getting additional information on the pre-processor calculations. This is useful to analyse more in detail the results and the characteristics of the scenario under study.

The tool generates some files, which are stored in a folder (see previous section), that can be analysed off-line (not part of the automated process of the network planning methodology). For example, the tool generates several graphics showing **statistical information** of lines' congestion, through the use of histograms and boxes and whisker plots for the main output parameters of the OPF simulation and others elaborated from them: LM, LMP, number of consecutive congestion hours for a line, etc.

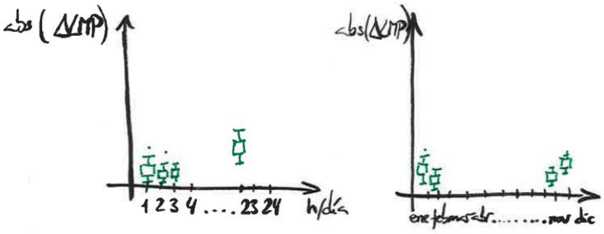

Figure 3.1 – Branches' statistical information graphs (for debugging purposes)

Also, the **congested lines location** in the network can be shown graphically, e.g., in Google Maps, through lines connecting the geographically identified buses in the network model (the geographical information of the nodes is necessary to permit this function).

Figure 3.2 – Congestion location identification example in Google Maps (for debugging purposes)

In addition, in order to assess the computational capacity of the planning tool, a parameter is used to fix the maximum number of candidates, considering these as arrays including location, technology, size and price. Other parameters are also used to control the number of outputs for the planning tool, such as: the number of selected congested lines and the maximum number of candidates selected from the influence of a congested line.

4 Preliminary validation tests and results

To test the methodology, a first use case was run based on the regional cases but considering the available information at that time:

- The planning tool was not fully operational and, therefore, some inputs needed for the pre-processor tool, such as the PTDFs, were not available.
- The grid models and scenarios are not totally translated to JSON format, as requested by the planning tool, so a whole year (8760 hours) was not tested.
- Distribution networks were not available yet and the sub-transmission was not been considered, since no scenario information was available. Just the transmission network was considered as input (220 and 400kV and around 820 nodes).

To check that the pre-processor was working in accordance to the described methodology, the following steps were taken:

- **Calculate PTDF values for the Spanish transmission network**: we used the DIgSILENT Power Factory (DPF) [4] network simulation tool to obtain the PTDF values for the Spanish transmission network, as provided by ENTSOE (from the *.raw* input file).
- **Create hourly "congested scenarios"**: the ENTSOE model provides a "screenshot" of the system, i.e. a one-hour scenario. This scenario refers to a Saturday (date 14/03/2020, 16:00h) and no congestions were observed (Lagrange Multipliers[5] of all branches are 0). We modified loads in the system to create six congested one-hour scenarios.
- **Create a use case out of the hourly congested and non-congested scenarios**: the six "congested scenarios" were combined with a base case (one-hour non-congestion scenario) to create a use case of around 40 hours.
- **Run the pre-processor algorithms**: the previous use case was used as input for the pre-processor and the later provided candidate flexibility options as result.

The use case preparation, in particular, the use of the DPF tool to calculate the PTDFs, permitted to make some preliminary observations:

- The algorithm considers a fixed variable-cost-factor [$/MWh] per generator, even if a cost curve is introduced as input (USD vs. MW).
- According to the theory of DC OPFs, the Locational Marginal Prices (LMP) that appear when no congestion exists should be the marginal cost of energy at the reference bus (slack) for all nodes. We checked the results, and this is what happens (49.423 USD/MWh in the example below, Figure 4.1).
- The LMP of a node in the network is affected by the value of the LMP at the slack node, by the LMs of all the branches that are in the path of the power flow between that node and the slack, and by the PTDFs affecting to those branches, which indicate the fraction of the power that

[5] In the DPF, the concept of shadow prices is used. Flowgate Shadow Prices (FSP) are defined in the theory, [1], as the difference of upper and lower Lagrange Multipliers (LM) of a branch (l): $\mu_l^{up} - \mu_l^{low}$

flows through each of the lines. This causes that, even if a congestion does not exist in a line (LM=0), there may exist a difference in the LMP value of its both nodes, in meshed networks.

- When the load is raised uniformly in the whole system, the generation accommodates without creating any congestion (using the slack), until the balance between demand and generation cannot be met. In this last case, the simulation does not converge.
- Congestion is created by increasing the all loads of the system and, also, loads at certain network ends, which led to obtaining 6 one-hour congestion scenarios.

An example of the Shadow prices or LM of the branches for one of the scenarios is shown in the next Figure 4.1

Name	Grid	Locational marginal price Terminal i in USD/MWh	Locational marginal price Terminal j in USD/MWh	System lambda Terminal i in USD/MWh	Loading %	Shadow price USD/MWh	Active Power Terminal i in MW
lne_616_907_1	1 ES	-11,411774879	183,91756356	49,423300691	100,	-203,2276	400,00015538
lne_797_1564_1	1 ES	46,241509255	50,599231463	49,423300691	100,	-4,357722	329,99999421
lne_1703_1709_1	1 ES	48,709877792	49,327641351	49,423300691	100,	-0,8056967	429,99984981
lne_833_1555_1	1 ES	47,911157003	54,001467761	49,423300691	100,	-6,809913	500,00011904
lne_788_1573_1	1 ES	52,42029061	48,732164741	49,423300691	100,	-4,534936	-419,99993465
lne_1809_1817_1	1 ES	48,978288157	49,091509255	49,423300691	100,	-0,4330642	290,00003815
lne_1809_1817_2	1 ES	48,978288157	49,091509255	49,423300691	100,	0,	290,00003815
lne_1352_2345_1	1 ES	28,787724595	183,97038119	49,423300691	100,	-158,7163	450,00008012
lne_608_1666_1	1 ES	58,697097935	58,697097935	49,423300691	100,	0,	-360,
lne_1666_1688_1	1 ES	58,697097935	58,697097935	49,423300691	100,	0,	-359,99999999
lne_1371_1744_1	1 ES	63,828920917	34,647086032	49,423300691	99,9999	-33,45997	-559,99983266
lne_645_1819_1	1 ES	49,085666525	49,083037923	49,423300691	96,5136	0,	-1669,686502
lne_618_1803_1	1 ES	-4,4118878694	0,64150925457	49,423300691	94,5745	0,	-435,04315464
lne_1199_1232_1	1 ES	48,889355041	48,889355041	49,423300691	92,2363	0,	350,49817508
lne_1371_1592_1	1 ES	63,828920917	50,171471658	49,423300691	91,8101	0,	-367,24083136
lne_779_788_1	1 ES	50,161865169	52,42029061	49,423300691	90,6845	0,	299,25907949
lne_616_618_1	1 ES	-11,411774879	-4,4118878694	49,423300691	89,6927	0,	-412,58665554
lne_1520_1817_1	1 ES	49,010509236	49,091509255	49,423300691	88,4299	0,	495,2075184
lne_1809_1811_1	1 ES	48,978288157	48,978288157	49,423300691	83,6655	0,	-123,82499994
lne_1224_1677_1	1 ES	48,846777996	48,846777996	49,423300691	83,5056	0,	-275,56850786
lne_1025_1126_1	1 ES	50,616317063	52,591102618	49,423300691	80,9796	0,	445,38834494
lne_1175_1745_1	1 ES	57,582772535	54,465926848	49,423300691	77,4897	0,	-294,46106175
lne_647_1817_3	1 ES	49,089710761	49,091509255	49,423300691	73,9428	0,	-258,79999494
lne_647_1817_4	1 ES	49,089710761	49,091509255	49,423300691	73,9428	0,	-258,79999494
lne_1095_1688_1	1 ES	48,844000156	58,697097935	49,423300691	72,8752	0,	492,63683337
lne_765_1063_2	1 ES	32,007166036	29,505080752	49,423300691	71,9407	0,	258,98683129
lne_1116_1129_1	1 ES	49,134668075	49,114606159	49,423300691	70,6553	0,	346,21147673
lne_634_880_1	1 ES	49,118033548	49,118033548	49,423300691	69,3364	0,	221,87650695
lne_1115_1130_1	1 ES	49,109647877	49,108739407	49,423300691	67,8688	0,	1140,1971811

Figure 4.1 – LM results for a one-hour scenario (part of the analysed use case)

Running the pre-processor provided results in form of a list of candidates. Some examples are presented below. The fist is a sodium sulphur battery candidate in node “S.P. Pinatar” (no. 1555, in Figure 4.1).

```
"storage": {
    "id": "NaSBattery_SP_Pinatar_220",
    "acBusConnected": "SP_Pinatar_220",
    "maxEnergy": [
        {
            "year": 2030,
            "value": 20.0
        }
    ],
    "selfDischargeRate": [
        {
            "year": 2030,
            "value": 0
        }
    ],
    "minEnergy": [
        {
            "year": 2030,
            "value": 4.0
        }
    ],
    "initEnergy": [
        {
            "year": 2030,
            "value": 10.0
        }
    ],
    "maxEnergyYear": [
        {
            "year": 2030,
            "value": 16000.0
        }
    ],
    "maxAbsPower": [
        {
            "year": 2030,
            "value": 10.0
        }
    ],
    "maxInjPower": [
        {
            "year": 2030,
            "value": 10.0
        }
    ],
    "absEfficiency": [
        {
            "year": 2030,
            "value": 0.9
        }
    "injEfficiency": [
        {
            "year": 2030,
            "value": 0.9
        }
    ],
    "maxAbsRamp": [
        {
            "year": 0,
            "value": 0
        }
    ],
    "maxInjRamp": [
        {
            "year": 0,
            "value": 0
        }
    ]
},
"invCost": [
    {
        "year": 2030,
        "value": 6000000.0
    }
```


Figure 4.2 – NaS battery candidate for node S.P. Pinatar

For this same node other candidates were proposed, for the planning tool to select the optimum solution among them: AC branch, PST, lithium battery, flow battery and hydrogen.

The next example is a candidate AC branch derived from the influence of a congested line.


```
{
    "acBranch": {
        "id": "AC____Influ_Aldeadavila_400_Villarino_400",
        "acBusOrigin": "Aldeadavila_400",
        "acBusExtremity": "Villarino_400",
        "isTransmission": true,
        "susceptance": 0,
        "voltageTapRatio": 0,
        "maxAngleDifference": 0,
        "minAngleDifference": 0,
        "resistance": 0,
        "reactance": 0,
        "meanTimeToRepair": 0,
        "failureRate": 0,
        "emergencyRating": 0,
        "ratedApparentPower": [
            {
                "year": 2030,
                "value": 1730
            }
        ]
    },
    "invCost": [
        {
            "year": 0,
            "value": 0
        }
    ]
},
```


Figure 4.3 – AC line candidate as influence of a congested line

In this case, this would be an example of the information that would be provided to the WP1 routing tool to be completed by it, in terms of characteristics and cost.

A second set of tests were done after a newer version of the planning tool was able to provide PTDF values. In this case, instead of the Spanish network case, the IEEE 6-bus system as defined in [15] was used as reference case. This is the transmission test system used in FlexPlan WP1 to perform tests related to the planning tool development [16].

The main files used by the pre-processor for this test are the following (JSON format):

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

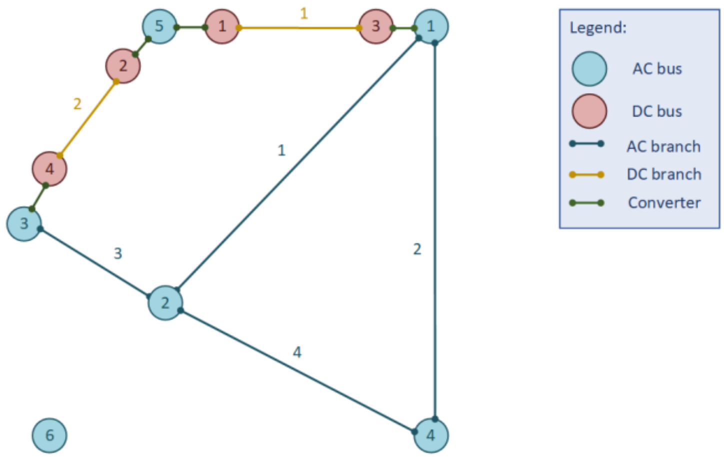

Figure 4.4 –IEEE 6 bus system

- OPF Output file from the 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 have some sort of congestion in that period. However branch 4 has very small values (under 10^{-10}). Branch 3 in the model shows high congestion and its LM values are represented in the following graph.

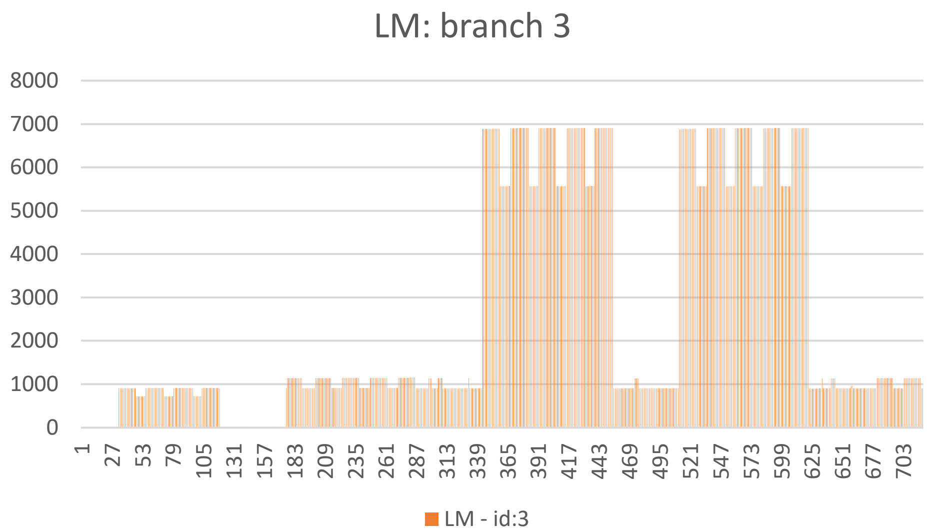

Figure 4.5 – LM values of branch 3 of the IEEE 6 bus system (output from the planning tool)

Considering the previous inputs, the pre-processor provides the following candidates for network expansion, in the JSON format required by the planning tool:

- 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 are considered as congestions. In addition, branch 1 was also selected as candidate due to the influence of one of the other branches. The JSON formats for the 3 branches in AC and DC, plus the converters linked to the latter, are generated to be shared with the online routing tool. This interface between tools is not operating yet.
- Two storages are proposed as candidate by the tool in node 2, one because of branch 3 and the other because of branch 4. Only one technology is 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 are not totally characterized, and, in this case, there is no information about water or caverns availability, so these technologies are not candidate.

- A flexible load is proposed in bus 2, because a load characteristic was introduced in that bus to test the tool.

The figures below show an equivalent of Figure 4.5, calculated by the pre-processor tool, and a statistical representation of those values, for both branches 3 and 4.

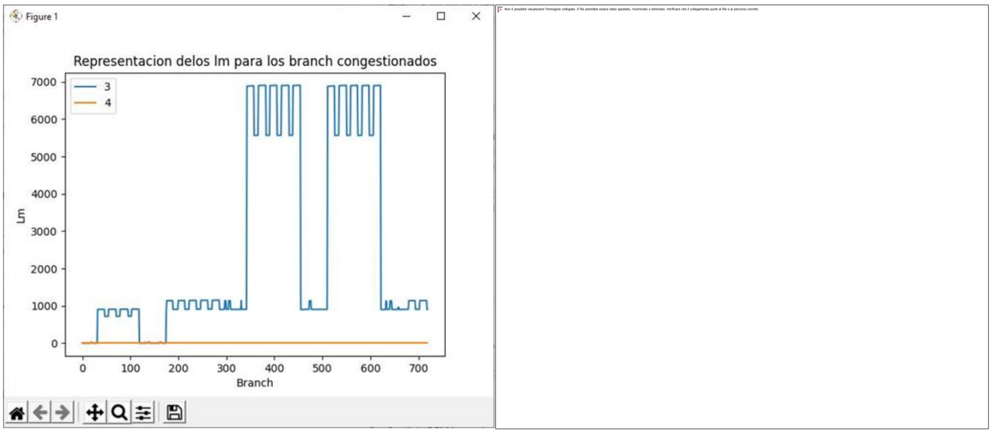

Figure 4.6 – LM values of branch 3 and 4 (left) and statistically (right) as result of the pre-processor

The following figure shows the congested lines in a map.

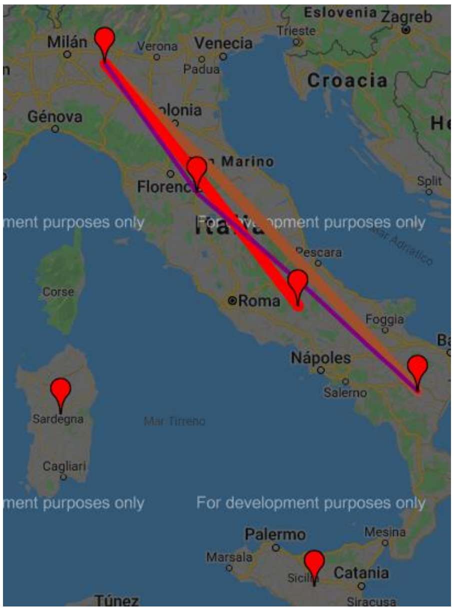

Figure 4.7 – Map showing the congested branches (red and orange)

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6 Annex I – Locational and congestion constraints

Technology		Bus related characteristics and constraints															
		Type of bus				Resources		Location of bus					Restriction (1)	Congestion duration (6)			
		Substation		Load	Power Plant	no water	no cavern	urban	industrial area	semi-rural	Rural			<2 hours	2-6 hours	>6 hours	Yearly
		air	under								Plain	Mountain					>4380 h
Batteries	Li-ion			(2)	(2)												
	NaS			(2)	(2)												
	Flow			(2)	(2)												
Demand Response	Total (aggregated per zones)	(3)	(3)	(4)				(3)	(3)	(3)	(3)	(3)					
	Industrial (per facility)	(3)	(3)	(4)				(3)	(3)	(3)	(3)	(3)					
Hydrogen				(2)	(2)												
Pumped hydro				(2)	(5)												
Compressed air storage																	
Liquid-Air Electricity Storage systems																	
PST																	
Lines	AC overhead																
	AC underground (cable)																
	HVDC																
Transformer, converter																	

(1) Restriction to build new facilities. It could be total or partial for certain technology (such as batteries, hydrogen, lines or substation)
(2) When the bus is specific of loads and/or generators, the decision to install storage should be of the owners of the plant and not of the regulator. SOs set connection conditions and third parties decide how to meet them.
(3) Loads connected to substations can be of different types: mostly residential, mostly commercial, mostly industrial, big industrial (specific big facilities), mixed
(4) Industrial loads can be of different types, e.g.: metal, paper, textile, cement, water treatment, gas industry, mining, shipyard, high speed train, automotive, chemical, hydrogen, other.
(5) When it is already a hydro plant it could be "suitable" to upgrade (build a reservoir, increase capacity)
(6) Congestion duration could be considered as: average duration in hours of congestion, maximum duration of congestion, % of hours of congestion in a day…

Table 6-1 – Locational constraints and bus characteristics

7 Annex II – Standard sizes and cost for flexible resources

Batteries	ID	Size depending on branch rating			Maximum and minimum size per technology (MVA)					
		2030	2040	2050	2030		2040		2050	
		as % of the congested branch power rating			Min	Max	Min	Max	Min	Max
Li-ion batteries	LiBattery	2%	3%	4%	0.1	450*	0.1	700*	0.1	1000*
NaS batteries	NaSBattery	2%	3%	4%	1.2	220*	1.2	330*	1.2	440*
Flow batteries	FlowBattery	2%	3%	4%	0.01	600*	0.01	900*	0.01	1200*
Hydrogen	H2	2%	3%	4%	1.5	200*	1.5	300*	1.5	400*
Pumped-storage hydro	PSH	2%	3%	4%	100	3500*	100	5250*	100	7000*
Compressed air storage	CAES	2%	3%	4%	0.01	330*	0.01	330*	0.01	330*
Liquid-Air Electricity Storage systems	LAES	2%	3%	4%	0.3	100*	0.3	150*	0.3	200*

* Size extrapolated from the present available maximum size by cost factor for the corresponding years

Table 7-1 – Size of storage [3]

Batteries	Cost								
	2030			2040			2050		
	CAPEX		OPEX	CAPEX		OPEX	CAPEX		OPEX
	€/kW	€/kWh	€/kWh	€/kW	€/kWh	€/kWh	€/kW	€/kWh	€/kWh
Li-ion	300	300	0.5% CAPEX	225	225	0.5% CAPEX	150	150	0.5% CAPEX
NaS	200	200	0.5% CAPEX	155	155	0.5% CAPEX	110	110	0.5% CAPEX
Flow	200	200	0.5% CAPEX	155	155	0.5% CAPEX	110	110	0.5% CAPEX

All costs were extrapolated from the present cost and future indicative cost in D2.2 [3]

Table 7-2 – Cost of batteries

Other storage	Cost					
	2030		2040		2050	
	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)
Hydrogen	500	2% CAPEX	450	2% CAPEX	400	2% CAPEX
Pumped hydro	50	0.5% CAPEX	40	0.5% CAPEX	30	0.5% CAPEX
Compressed air storage	60	0.23	60	0.23	60	0.23
Liquid-Air Electricity Storage systems	175	0.5% CAPEX	135	0.5% CAPEX	95	0.5% CAPEX

Table 7-3 – Cost of other storage [3]

Demand Response activities (big consumers)	Standard demand reduction			Cost (per year)					
	2030	2040	2050	2030		2040		2050	
	kW	kW	kW	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)
Sawmills and Wood Preservation	1799	1799	1799	29	17	22	13	15	9
Non-metallic Mineral Mining and Quarrying	1000 [5] [6]	1000 [5] [6]	1000 [5] [6]						
Converted Paper Product Manufacturing	1133	1133	1133						
Cement	1000	1000	1000						
Fruit and Vegetable Preserving and Specialty Food Manufacturing	881	881	881						
Agriculture, Construction and Mining Machinery Manufacturing	865	865	865						
Basic Chemical Manufacturing	623	623	623						
Other Electrical Equipment and Component Manufacturing	583	583	583						
Resin, Synthetic Rubber and Artificial Synthetic Fibres and Filaments Manufacturing	546	546	546						
Other General Merchandise Stores	523	523	523						
Dairy Product Manufacturing	333 [5] [6]	333 [5] [6]	333 [5] [6]						
Support Activities for Crop Production	490	490	490						
Aerospace Product and Parts Manufacturing	472	472	472						
Other Fabricated Metal Product Manufacturing	384	384	384						

Animal Slaughtering and Processing	372	372	372						
Other Textile Product Mills	303	303	303						
Steel Product Manufacturing from Purchased Steel	299	299	299						
Water, Sewage and other systems	286	286	286						
Bakeries and Tortilla Manufacturing	277	277	277						
Cattle Ranching and Farming	255	255	255						
Beverage Manufacturing	244	244	244						
Pulp, Paper and Paperboard Mills	240	240	240						
Clay Product and Refractory Manufacturing	220	220	220						
Other General Purpose Machinery Manufacturing	211	211	211						
Warehousing and Storage	209	209	209						
Plastic manufacture industry	300 [6]	300 [6]	300 [6]						
Printing/Graphic industry	280 [6]	280 [6]	280 [6]						
Hotel	260 [6]	260 [6]	260 [6]						
Hospital	300 [6]	300 [6]	300 [6]						
Supermarket	60 [6]	60 [6]	60 [6]						
Rest industrial and commercial (1)	50	50	50						

(1) Proposed for big industrial and commercial with no activity specified.

Table 7-4 – Standard demand reduction and cost of industrial and commercial DR (elaborated from [5] and [6])

Demand Response activities (small consumers in distribution)	Standard demand reduction			Cost (per year)					
	2030	2040	2050	2030		2040		2050	
	as % of total load			CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)
mostly residential	0.5%	2%	5%	29	17	22	13	15	9
mostly commercial	5%	10%	15%						
mostly industrial	10%	20%	25%						
mixed	4%	8%	13%						

Small consumers were not meant to be considered within FlexPlan. At this point, these numbers are "invented", as example to consider if it is worth to take them into account (for sensibility studies, for example).

Table 7-5 – Standard demand reduction and cost of small consumers in distribution networks

8 Annex III – Bottleneck calculation in meshed networks

A methodology has been proposed to avoid, in meshed networks, that solving the congestion in one branch may cause that others become congested in its surroundings. This would mean that the investment to upgrade the network has not turned out to be effective.

We use the Power Transfer Distribution Factors (PTDF) of the network to check how the increase of capacity in one line affects the saturation in other lines in this defined influence area.

We consider an injection of power in node K_1 and the same extraction of power in K_2 of the network and that the power constraint in the lines is relaxed (power flow can go over the rated capacity of the line).

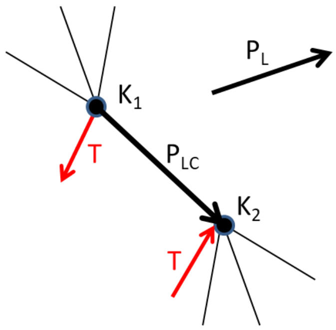

Figure 8.1 – PTDF analysis approach

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 line, *l*, within the influence area:

$$P_l - P_l^0 = T\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right) \quad (3)$$

$$P_{lc} - P_{lc}^{max} = T\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right) \quad (4)$$

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

$$P_{lc} - P_{lc}^{max} = \frac{\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right)}{\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right)}(P_l - P_l^0) \quad (5)$$

We focus on the moment when the power flow in *l* reaches its maximum capacity (i.e., $p_l = p_l^{max}$). At this stage, the power in *lc* is noted, $p_{lc}*$.

$$P_{lc}^* - P_{lc}^{max} = \frac{\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right)}{\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right)}(P_l^{max} - P_l^0) \quad (6)$$

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

$$\alpha_{l,lc} = \frac{P_{lc}^* - P_{lc}^{max}}{P_{lc}^{max}} = \frac{\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right)}{\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right)}\frac{(P_l^{max} - P_l^0)}{P_{lc}^{max}} \quad (7)$$

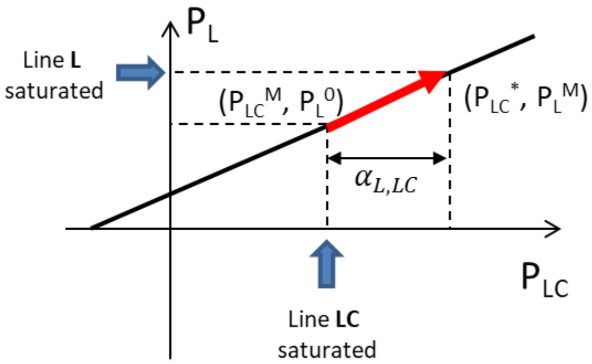

Figure 8.2 – Relationship between the saturation of the congested line and of a line in the influence area

The lines with higher risk to become congested are those with lower values of $\alpha_{l,lc}$.

9 Annex IV – Standard costs for lines, transformers and converters

Lines	Overhead/underground (€/km)
380-400 kV, 2 circuit	1.050.000
380-400 kV, 1 circuit	600.000
220-225 kV, 2 circuit	400.000
220-225 kV, 1 circuit	280.000
	Subsea (€/km)
All cables types	900.000
AC cables	1.100.000
DC cables	750.000

Table 9-1 – Standard cost of lines (Source: ELES)

Transformer	€/MVA
Cost per total rating (MVA)	9.900
Total cost per capacity	€
500-800 MVA	6.100.000
300-450 MVA	3.800.000
150-280 MVA	1.800.600

Table 9-2 – Transformer costs (Source: ELES)

Converter	€/MVA
Cost per total rating (MVA)	
1-4 converter transformers	87.100
6-8 converter transformers	155.000

Table 9-3 – HVDC converter station costs (Source: ELES)

10 Annex V –PST

Technology	Cost (per year)											
	2030						150kV					
	kV?*		400kV**		150kV***		2030		2040		2050	
	CAPEX (€/kW)	OPEX (€/kW)	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)
PST	Up to 35	0,15 €/kW	10-40		13.33							

* Source: ELES

**400 kV, 100-1600 MVAR/MVA [7]

***400/150kV, 450MVA, transformer including PST at 150kV: 6M€ (Source: REN)

Table 10-1 –Cost of PST

PST size (MVA)	%Z (minimum)
< 0.63	4
0.63 – 1.25	5
1.25 – 2.5	6
2.5 - 6.3	7
6.3 – 25	8
25 – 40	10
40 – 63	11
63 - 100	12.5
> 100	> 12.5

Table 10-2 –Impedance of PSTs [11]

11 Annex VI –Other parameters of lines, converters and transformers

Technology	mean time to repair (MTTR) (h)	failure rate (1/year)	long term emergency rating (times the normal rating)
AC overhead	10.81	0.39	1.20
AC underground (cable)	14.43	0.38	1.16
Transformer	768	0.02	1.28
HVDC line	26.01	1.61	1 (no data available)
Converter	26.01	1.61	1 (no data available)
PST	768	0.02	1.24
Generator (hydro)	20	0.01	1 (no data available)
Generator (nuclear, LWR)	150	0.12	1 (no data available)
Generator (Thermal, oil/coal)	53	0.04	1 (no data available)

Table 11-1 –Mean time to repair, failure rate and emergency rating information [12][13][14]

12 Annex VII – Codes for restrictions/characteristics of bus fields

Type of bus	Code	Comment
Substation (air)	SBSTAIRR	Default value: If no bus type is provided
Substation air compact	SBSTCPCT	
Substation underground	SBSTUNDG	
Power Plant: wind	PWPLWIND	
Power Plant photovoltaic	PWPLPVPV	
Power Plant biomass	PWPLBMSS	
Power Plant hydro	PWPLHYDR	
Power Plant thermal conventional	PWPLTHRM	
Power Plant Combined Cycle	PWPLCCYC	
Power Plant thermal nuclear	PWPLNCLR	
Commercial load	CMCLLOAD	Not specified commercial load (not under the classification below)
Industrial load	INDLLOAD	Not specified industrial load (not under the classification below)
Sawmills and Wood Preservation	INDLSWMW	
Non-metallic Mineral Mining and Quarrying	INDLNMMM	
Converted Paper Product Manufacturing	INDLPPMN	
Cement	INDLCMNT	
Fruit and Vegetable Preserving and Specialty Food	INDLFRVG	

Manufacturing		
Agriculture, Construction and Mining Machinery Manufacturing	INDLACMN	
Basic Chemical Manufacturing	INDLCHMN	
Other Electrical Equipment and Component Manufacturing	INDLEEMN	
Resin, Synthetic Rubber and Artificial Synthetic Fibres and Filaments Manufacturing	INDLFFMN	
Dairy Product Manufacturing	INDLDPMN	
Support Activities for Crop Production	INDLCRPR	
Aerospace Product and Parts Manufacturing	INDLAPMN	
Other Fabricated Metal Product Manufacturing	INDLMPMN	
Animal Slaughtering and Processing	INDLASPR	
Other Textile Product Mills	INDLTXTM	
Steel Product Manufacturing from Purchased Steel	INDLSTMN	
Water, Sewage and other systems	INDLWTSW	
Bakeries and Tortilla Manufacturing	INDLBKMN	
Cattle Ranching and Farming	INDLCTFR	
Beverage Manufacturing	INDLBVMN	
Pulp, Paper and Paperboard Mills	INDLPPPM	

Clay Product and Refractory Manufacturing	INDLPRMN	
Other General Purpose Machinery Manufacturing	INDLMCMN	
Warehousing and Storage	INDLWHST	
Plastic manufacture industry	INDLPLMN	
Printing/Graphic industry	INDLPRGR	
Other General Merchandise Stores	COMMMRST	
Hotel	COMMHOTL	
Hospital	COMMHPTL	
Supermarket	COMMSPMT	
Availability of Natural Resources		
Water	RSRCWATR	River, reservoir
Wind	RSRCWIND	Area with wind parks near
Sun	RSRCSUNN	Solar power plants near
Biomass	RSRCBMSS	
Cavern	RSRCCVRN	
Loads supplied (for Substations)		
Mainly Residential	RSDTLOAD	
Mainly commercial	CMCLLOAD	
Mainly Industrial	INDLLOAD	

Mixed	MIXDLOAD	Default value if none is indicated
Big industrial	As above	
Location of bus (if no value, no restriction)		
Urban (populated city)	LCTNURBN	Default value: no restriction (if no value is provided, no restriction is considered)
Semi-rural (outskirts of populated city, small city)	LCTNSMRR	
Rural	LCTNRURL	
Industrial area	LCTNINAR	
Geographic characteristics (for rural buses)		
Mountainous	LCTNMNTN	Default value: no restriction (if no value is provided, no restriction is considered)
Hilly	LCTNHILL	
Plain	LCTNPLAI	
Restricted area (not allowed to build new installations): for lines; for hydro plants; for hydrogen; for batteries; for CAES/LAES; total restriction.		
For lines	RSTRLINE	Default value: no restriction (if no value is provided, no restriction is considered)
For hydro plants	RSTRPPHY	
For hydrogen	RSTRHDRG	
For batteries	RSTRBTTR	
For CAES/LAES	RSTRCAES	
Total restriction	RSTRTOTL	

Table 12-1 – Bus description codes

13 Annex VIII – Planning tool candidate data models

Data model fiels	Li-ion			NaS			Flow battery		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
id	LiBattery_BusConnected			NaSBattery_BusConnected			FlowBattery_BusConnected		
acBusConnected	From pre-processor results			From pre-processor results			From pre-processor results		
maxEnergy (MWh)	From pre-processor results			From pre-processor results			From pre-processor results		
selfDischargeRate (p.u. per hour) [8]	0.0056*	0.0056*	0.0056*	0	0	0	0	0	0
minEnergy (MWh)	20%?	20%?	20%?	20%?	20%?	20%?	10%	10%	10%
initEnergy (MWh)	50%	50%	50%	50%	50%	50%	50%	50%	50%
maxEnergyYear (MWh) (elaborated from on [9])	1000 FCE**	2000 FCE**	3000 FCE**	1000	2000	3000	2000	3000	4000
absEfficiency (p.u.)***	0.94	0.96	0.98	0.90	0.93	0.95	0.72	0.74	0.75
injEfficiency (p.u.)	0.94	0.96	0.98	0.90	0.93	0.95	0.72	0.74	0.75
maxAbsRamp (MW/h)	-	-	-	-	-	-	-	-	-
maxInRamp (MW/h)	-	-	-	-	-	-	-	-	-
maxReactivePowerExchange (MVAr)	33%*P	33%*P	33%*P	33%*P	33%*P	33%*P	33%*P	33%*P	33%*P
minReactivePowerExchange (MVAr)	-33% P	-33% P	-33% P	-33% P	-33% P	-33% P	-33% P	-33% P	-33% P
Investment cost (€) ****	From pre-processor results			From pre-processor results			From pre-processor results		
Scenario									
PowerExternalProcess (MWh, time series)	0			0			0		
Status (1/0)	1			1			1		
maxAbsPower (MW)	From pre-processor results			From pre-processor results			From pre-processor results		
maxInjPower (MW)	equal to max. abs power			equal to max. abs power			equal to max. abs power		

*4% per month

**FCE: Full Cycle Equivalent

***Converter efficiency should be included in the storage efficiency

****CAPEX. OPEX is assumed to be zero

Table 13-1 –Batteries candidate data model (elaborated from [3] references, where not stated differently)

Data model fiels	Hydrogen			Pumped Hydro		
	2030	2040	2050	2030	2040	2050
id	H2_BusConnected			PSH_BusConnected		
acBusConnected	From pre-processor results			From pre-processor results		
maxEnergy (MWh)	From pre-processor results			From pre-processor results		
selfDischargeRate (p.u. per hour)	0	0	0	0	0	0
minEnergy (MWh)	0%	0%	0%	0%	0%	0%
initEnergy (MWh)	50%	50%	50%	50%	50%	50%
maxEnergyYear (MWh)	4000 hours*	unlimited**	unlimited**	unlimited**	unlimited**	unlimited**
absEfficiency (p.u.)	0.82***	0.85	0.85	0.89	0.89	0.89
injEfficiency (p.u.)	0.50***	0.55	0.60	0.89	0.89	0.89
maxAbsRamp (MW/h)	-	-	-	-	-	-
maxInRamp (MW/h)	-	-	-	-	-	-
maxReactivePowerExchange (MVAr)	33%*P	33%*P	33%*P	33%*P	33%*P	33%*P
minReactivePowerExchange (MVAr)	-33% P	-33% P	-33% P	-33% P	-33% P	-33% P
Investment cost (€)	From pre-processor results			From pre-processor results		
Scenario						
PowerExternalProcess (MWh, time series)	0			From the scenario info****		
Status (1/0)	1			1		
maxAbsPower (MW)	From pre-processor results			0		
maxInjPower (MW)	equal to max. abs power			From pre-processor results		

* Limit established by the fuel cell which has currently the lowest lifetime [10]

**Considering that the charging and discharging processes take similar amount of time, to work more than half of the hours in a year can be considered unlimited.

*** Considering electricity – hydrogen – electricity cycle

****external inflow of energy, eg. a river delivering water to the reservoir

Table 13-2 –Hydrogen and Pumped hydro storage data models (elaborated from [3] references, where not stated differently)

Data model fiels	CAES			LAES		
	2030	2040	2050	2030	2040	2050
id	CAES_BusConnected			LAES_BusConnected		
acBusConnected	From pre-processor results			From pre-processor results		
maxEnergy (MWh)	From pre-processor results			From pre-processor results		
selfDischargeRate (p.u. per hour)	0	0	0	0	0	0
minEnergy (MWh)	50%	40%	20%	0%	0%	0%
initEnergy (MWh)	50%?	50%?	50%?	50%?	50%?	50%?
maxEnergyYear (MWh)	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
maxAbsPower (MW)	From pre-processor results			From pre-processor results		
maxInjPower (MW)	From pre-processor results			From pre-processor results		
absEfficiency (p.u.)	0.84	0.84	0.84	0.87	0.87	0.87
injEfficiency (p.u.)	0.84	0.84	0.84	0.87	0.87	0.87
maxAbsRamp (MW/h)	-	-	-	-	-	-
maxInRamp (MW/h)	-	-	-	-	-	-
maxReactivePowerExchange (MVAr)	33%*P	33%*P	33%*P	33%*P	33%*P	33%*P
minReactivePowerExchange (MVAr)	-33% P	-33% P	-33% P	-33% P	-33% P	-33% P
Investment cost (€)	From pre-processor results			From pre-processor results		
Scenario						
PowerExternalProcess (MWh, time series)	0			0		
Status (1/0)	1			1		
maxAbsPower (MW)	From pre-processor results			From pre-processor results		
maxInjPower (MW)	equal to max. abs power			equal to max. abs power		

Table 13-3 –CAES and LAES data model (elaborated from [3] references, where not stated differently)

Data model fiels	Flexible load		
	2030	2040	2050
id	Code_BusConnected		
acBusConnected	From pre-processor results		
power factor (p.u.) (for loads connected to distribution only)	0.9	0.9	0.9
gracePeriodUDS (h)*	18	18	18
gracePeriodDDS (h)*	18	18	18
maxEnergyNotConsumed (MWh)	0**		
invcost (€)	From Table 7-4		
Scenario			
Demand Reference (MW)	From scenario data		
curtailmentCosts (€/MW)	From scenario data		
Status	1 (default)		
Value of loss load (€/MWh)	From scenario data		

* UDS: first we increase consumption, later we decrease consumption
DDS: first we reduce consumption, later we increase it

****** We consider it zero, for the moment, meaning that all demand should be shifted. In the case of big consumers this might be close to reality, since processes are already efficient in order to reduce costs, so there is few space for demand reduction.

Investment cost: cost for the load to enable flexibility (which can cover the new energy management systems installation, for instance).

Curtailment cost: they are considerable bigger than demand shifting and not consumed energy costs. From a power system perspective, it represents the same as not consumed energy, with the difference that it is activated unilaterally by the System Operator when there is still need to reduce load. It should reflect a very high marginal cost of disconnecting loads against their will.

Value of lost load (VOLL): it reflects the value of load that has been interrupted, besides exploiting to the maximum the aforementioned mechanisms (demand shift, non consumption and curtailment). It is used to quantify the costs related to reliability of supply.

Table 13-4 –Flexible Load data model (elaborated from [3] references, where not stated differently)

Data model fields	AC Branch and transformer		
	2030	2040	2050
id	ACOHL_busFrom_busTo ACUGC_busFrom_busTo Transformer_busFrom_busTo		
acBusOrigin	From WP2 pre-processor results		
acBusExtremity	From WP2 pre-processor results		
isTransmission	From Grid Model (True/False)		
susceptance (Siemens)	From WP1 line routing tool for lines For WP2 similar to existing transformer		
resistance (Ohms)	From WP1 line routing tool for distribution line For transformer: WP2 similar to existing one		
reactance	From WP1 line routing tool for lines For transformer: WP2 similar to existing one		
voltageTapRatio	0 for lines For transformer: WP2 similar to existing one		
maxAngleDifference (rad)	2π		
minAngleDifference (rad)	-2π		
meantimeToRepair (h)	From table Table 11-1		
failureRate (1/year)	From table Table 11-1		
emergencyRating (MW)	From table Table 11-1		
ratedApparentPower (MVA)	From WP2 pre-processor results		
IsInterconnection	From Grid Model		
length	From WP1 line routing tool for lines		
InvestmentCost (€/MVA)	From WP1 line routing tool For transformers from Table 9-2		

Table 13-5 –AC Branches and transformers data model

Data model fiels	DC branch		
	2030	2040	2050
id	HVDC_busFrom_busTo		
dcBusOrigin	From WP2 pre-processor results		
dcBusExtremity	From WP2 pre-processor results		
ratedActivePower (MW)	From WP2 pre-processor results		
meantimeToRepair (h)	From table Table 11-1		
failureRate (1/year)	From table Table 11-1		
emergencyRating (MW)	From table Table 11-1		
IsInterconnection	From Grid Model		
length	From WP1 line routing tool for lines		
InvestmentCost (€/MVA)	From WP1 line routing tool		

Table 13-6 –DC Branches data model

Data model fields	Converter		
	2030	2040	2050
id	Converter_busFrom_busTo		
acBusConnected	From WP2 pre-processor results		
dcBusConnected	Fictitious node: acBusConnected +"_DC" code		
auxiliaryLosses (MW)	From WP1 line routing tool		
linearLosses (MW/MW)	From WP1 line routing tool		
ratedActivePowerAC (MW)	From WP2 pre-processor results		
ratedActivePowerDC (MW)	From WP2 pre-processor results		
meantimeToRepair (h)	From table Table 11-1		
failureRate (1/year)	From table Table 11-1		
emergencyRating (MW)	From table Table 11-1		
InvestmentCost (€/MVA)	From WP1 line routing tool		

LinearLosses = L_b, AuxiliaryLosses = L_a; P_ac + P_dc = P_losses = L_a + L_b*P_ac; P_ac * (1 - L_b) + P_dc = L_a

Table 13-7 –Converter data model

Data model fiels	PST		
	2030	2040	2050
id	PST_busFrom_busTo		
acBusOrigin	From WP2 pre-processor results		
acBusExtremity	From WP2 pre-processor results		
susceptance (Siemens)	From Table 10-2		
ratedActivePowerAC (MW)	From WP2 pre-processor results		
maxAngleDifference (rad)	2π		
minAngleDifference (rad)	-2π		
maxPhaseShift (rad)	0.78 (45°)		
minPhaseShift (rad)	-0.78 (45°)		
meantimeToRepair (h)	From table Table 11-1		
failureRate (1/year)	From table Table 11-1		
emergencyRating (MW)	From table Table 11-1		
InvestmentCost (€/MVA)	from Table 10-1		

Table 13-8 –Phase Shifting Transformers (PST) data model