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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			pumped hydro as candidate, line characteristics update (V vs. X), DR cost info updated.
1.9	09/08/2022	TECNALIA	Update of last decisions. Final tunning of the pre-processor
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1.12	13/09/2022	TECNALIA	Final modifications of values and bugs under validation from RSE: adaptation to the T&D decomposition JSON format, modification of X/length reference, modification in branch lifetime, modification on flexible loads investment costs

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) 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.

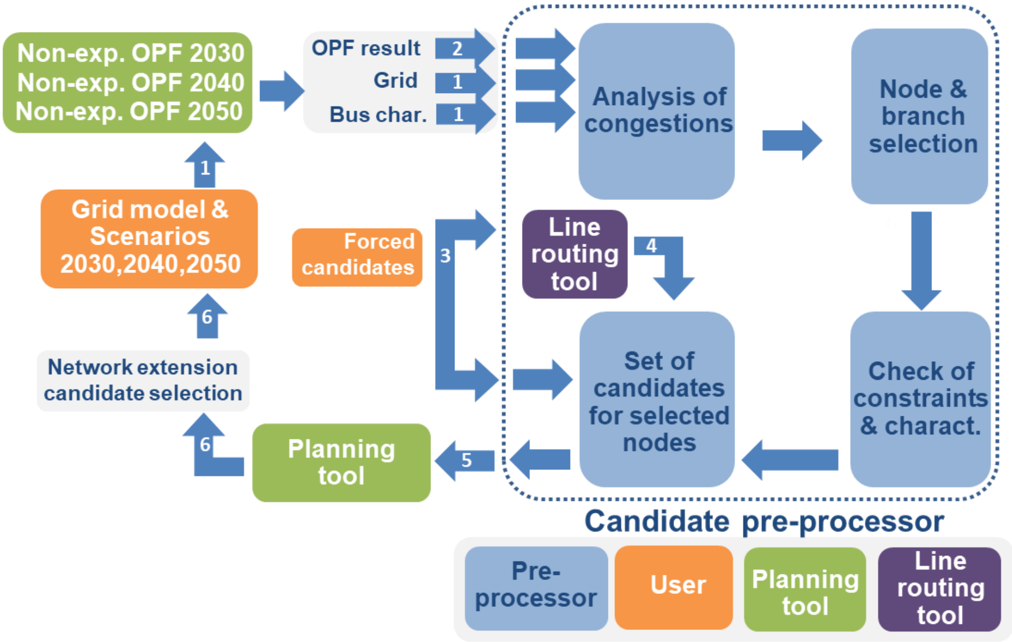

Figure 2.1 – Pre-processor tasks in relation to FlexPlan planning methodology

After the user has input a grid and scenario data, 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, section 6.3), is used to provide line candidates between two nodes or substations that were not previously connected. 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, 2040 and 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	Network model: • Grid • Scenario • Bus characteristics and constraints	User Planning tool (grid expansion)	JSON
2	Non- expanded network OPF results: • LMPs (Locational Marginal Prices) & LM (Lagrange Multipliers) • Power flows in branches resulting from the OPF • Power Transfer Distribution Factors (PTDF)	Planning tool	JSON
3	Candidates forced/proposed by the user	User	JSON
4	Technical characteristics and cost of candidate lines (for previously unconnected buses)	WP1 tool	JSON
5	Set of candidates for selected nodes	Pre-processor	JSON
6	Grid expansion results: accepted candidates	Planning tool	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 performed.

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

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

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 at 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.

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 linked to its extraction at another given 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 **AC 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 a minimum (currently, LMs lower than 0.001 are not considered as congestion).

[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].

b. Average LM value considering all year hours (sum of LM values for a branch, along the year).

After the simplifications considered in the final versions of the planning tool (4 weeks representative of each yearly variant and two hour time steps) this value is calculated taking this into consideration: each hour represents two, the 8 weeks representing one year (4 weeks each variant), the LM values are affected by their representativeness (the 8 weeks have a factor each that in total make them represent 52 weeks).

This is done for all variants of each scenario and year.

2. Based on the previous statistical results, a number of lines is selected, reflecting the **most congested lines** in the system. The number of total congestion hours for an element represents the **occurrence**. To take both severity and occurrence into account, the following factor is used: the **yearly average LM times the occurrence**. A common ranking is created for congestions considering all the variants. The probability assigned to each variant is also used to provide a weight to the congestions identified in each of them. 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.

The following Figure 2.2 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), in the general case (not simplified).

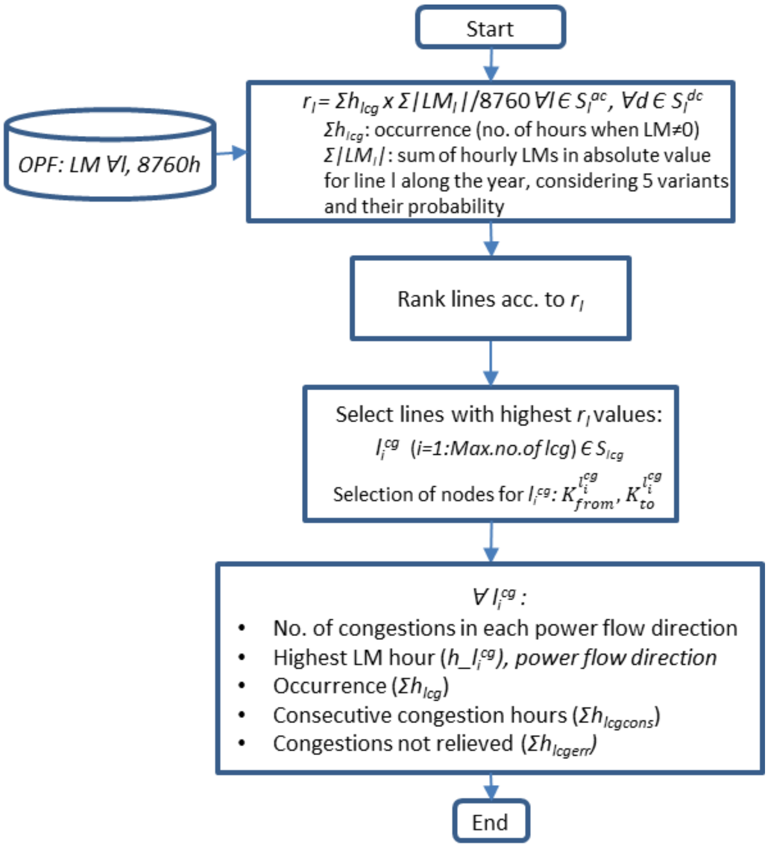

Figure 2.2 – Flow chart for the selection of congestion scenarios

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, compressed air storage (CAES) and liquid air storage (LAES). Pumped-hydro storage could be included as forced candidate (when allowed by the planning tool).
- **Demand Response** (DR): through flexible loads.
- **Conventional network assets**: lines/cables (AC) and transformers. HVDC storage could be included as forced candidate.
- **Phase-Shifting Transformers** (PSTs) is considered only as forced candidate (when allowed by the planning tool).

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 hydrogen; for batteries; for CAES/LAES; total restriction.
    - **Is interconnection:** to check if a certain branch is connecting two different countries/regions (initially, considered for PST installation).
- **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, lithium ion batteries 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. To end the process, the candidate pre-processor exchanges the *GridExpanssionPlanningInputFile* with the planning tool. The latter includes the candidates for grid expansion and new grid elements that might be necessary (e.g. buses).

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): forced candidates. 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). In this case, an external software for line routing between two nodes is used to identify the characteristics and cost of both AC and DC candidate lines. In the case of HVDC lines, PSTs and pumped-hydro plants, because they require a dedicated study, the pre-processor does not provide candidates automatically, but the candidates need to be defined as forced candidates by the user. The idea is that users could also propose other types of candidates, e.g. storage, independently from the results or the pre-processor calculation.

A maximum number of candidates is set to weight the computational capabilities of the planning tool. 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.

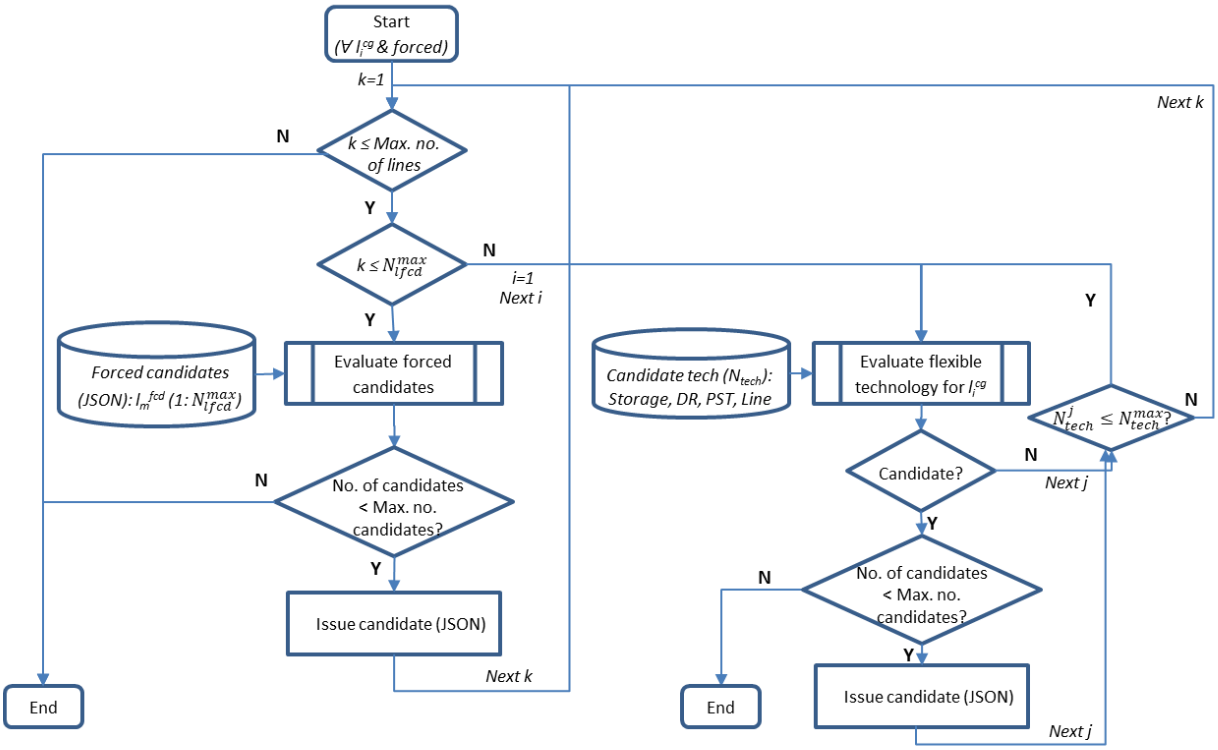

Figure 2.3 – Flow chart for the selection of candidates (general)

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 higher than a minimum (currently, 0.001).
    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.

    The data simplification considered in the final version of the planning methodology, affects this calculation, because 8760 hours are not available, but only 8 weeks representing 52 (whole year). The adopted implementation considers the following: the characteristics of one hour extended to the time step (e.g., if one hour is congested and the time step is two hours, this is considered as if two hours are congested one after the other); weekly representativeness is considered to calculate the yearly number of congestions; and to calculate the number of consecutive congestion hours the percentage of congestion hours not relieved, the 8 weeks are calculated in a row without their yearly representativeness.

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 is defined as a percentage of the annual number of congestion hours (e.g. 50%), as nominal power per annual hours. Also for CAES and LAES we consider, in principle, that the storage is able to store energy in the 50% of congestion hours.
5. In the case that **two or more congested lines meet at a selected 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 selected 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.

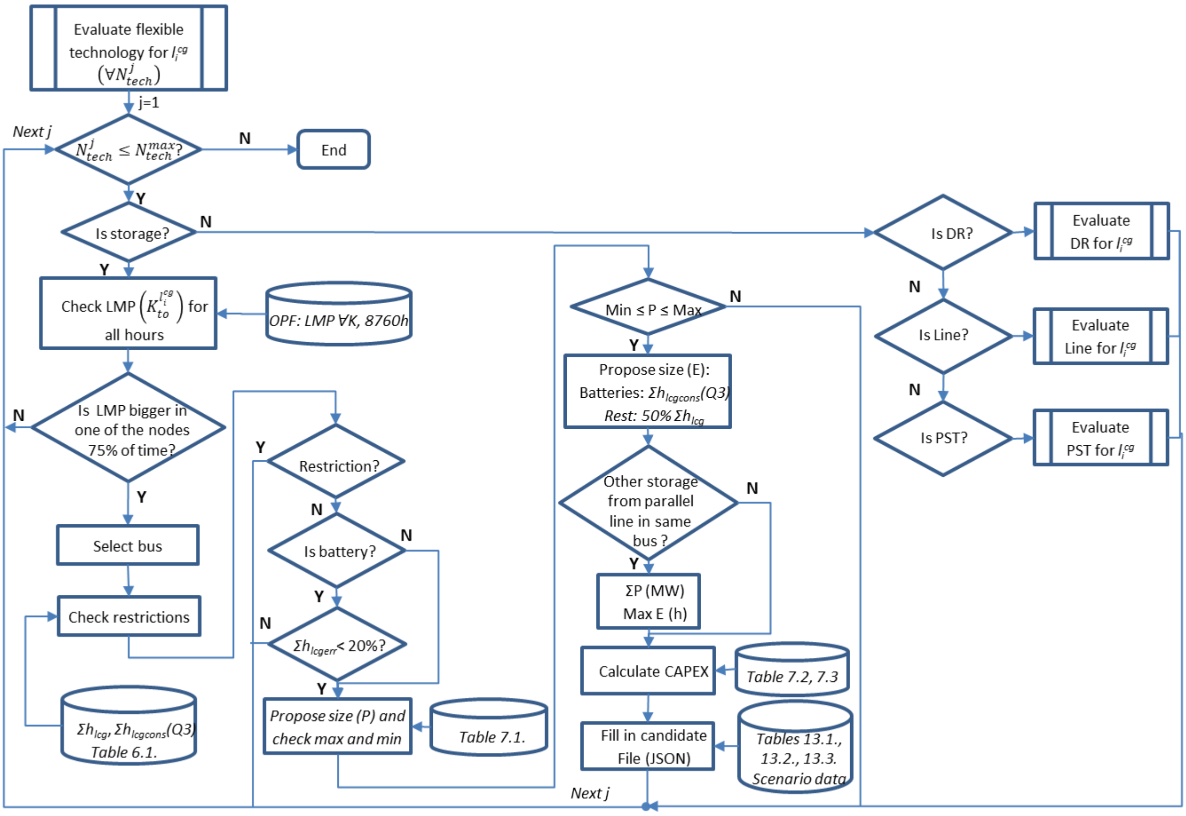

Figure 2.4 – Flow chart for the selection of candidates (flexibility and storage)

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, in more than 75% of the time, 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).
2. **Locational information** is checked for each of the selected nodes (Annex I), if:
    a. If no load is available, the node is not selected.
    b. If a 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 is proposed for the selected load type in accordance to Table 7-4 and Table 7-6, which is an input that can be modified. In the current version of the pre-processor, for transmission and sub-transmission lines, Table 7-5 is used, where industrial load

value is considered as default (it is used if the load has no commercial type specified). For distribution lines, Table 7-6 is considered where the default value is that for type "mixed" and it is the one used unless the load is defined as industrial or commercial (in this case, the values in the table for these types apply). Regarding the cost, this is also provided in Table 7-6., in the current version, it is considered very small but different to zero (it represents the cost for the DSO for transforming one load from not-flexible to flexible).

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

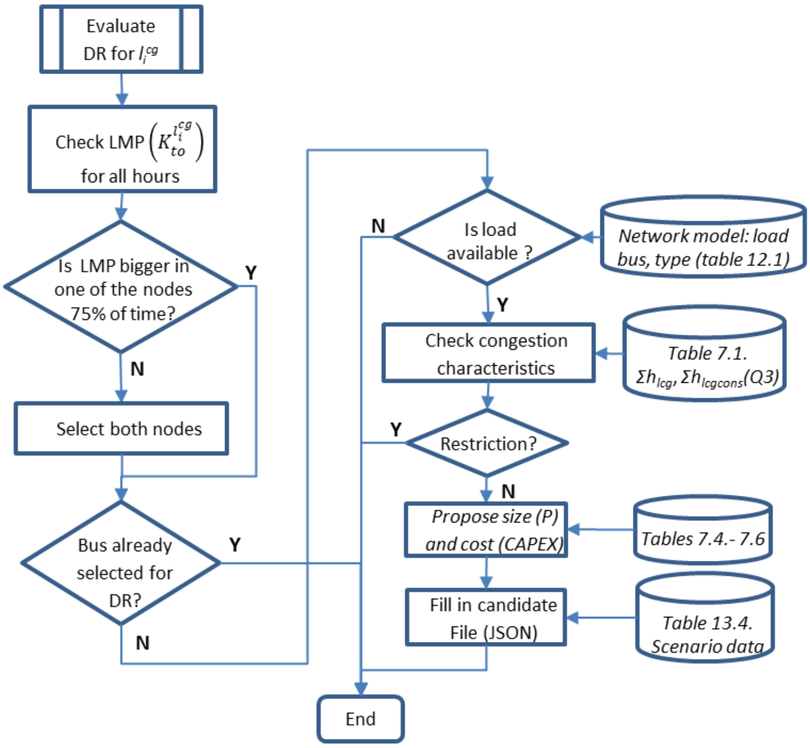

Figure 2.5 – Flow chart for the selection of candidates (DR/Flexible loads)

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.

The candidate pre-processor provides automatically only AC candidates. HVDC candidates need to be proposed as forced candidates.

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:

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 (6) 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:

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

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 (currently the limit is equal to 5) 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, an AC line with the **same characteristics** as those of the congested one is proposed. In transmission, we are following the approach of adding a new line between the nodes of the congested lines, however, in distribution, lines are substituted with double nominal power and half impedance. The same approach applies to transformers. 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. To provide a price for the AC line the following approaches are considered depending on the availability of data:
   a. Length available: an average cost of the line per km will be used to calculate the total cost (Table 9-4).
   b. No length available (e.g. distribution lines): information on average impedance per kilometre is considered to calculate a length from the impedance of the line/cable. In the current implementation, in Table 9-4, we consider "cable" value for distribution lines and "line" for transmission.

   To calculate the price (Table 9-3), in transmission, 1C or 2C is selected depending on the nominal current of the line. For distribution, as we are substituting the lines with double power, the 2C value is selected for the variable price (which has been selected two times the 1C value).

8. The **grid expansion planning 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 and transformer technologies.

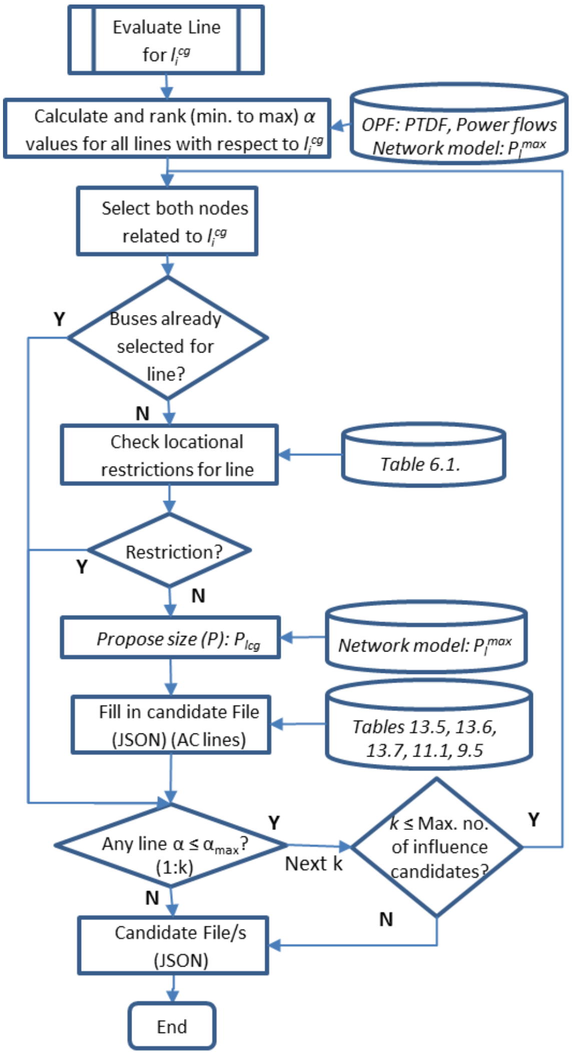

Figure 2.6 – Flow chart for the selection of candidates (AC and DC lines and transformers)

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, at least: *from* and *to* nodes, including geographical location, voltage level and power. The defined candidate file formats in JSON are used (as improvement to the current version of the planning tool, it would be better to provide all required data, but the electrical characteristics of the network and its price).

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 pre-processor pre-fills in templates according to the available information.
3. Once the information related to line candidates is complete , the **grid expansion planning input file** is handled over to the planning tool, including new DC buses for HVDC links if required.

The following flow chart represents graphically the steps above.

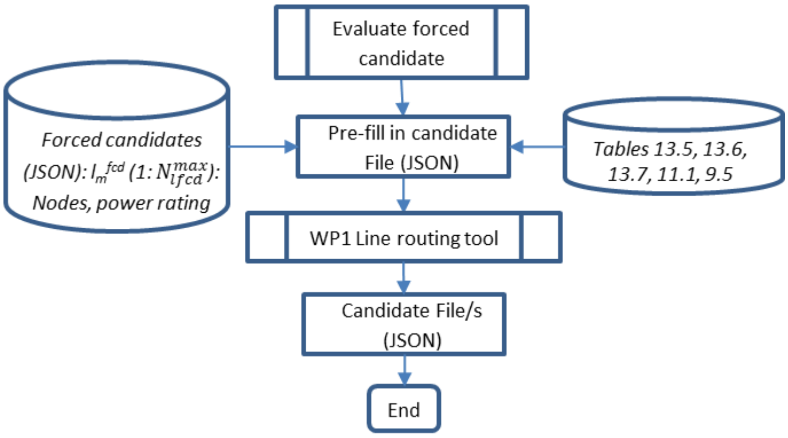

Figure 2.7 – Flow chart for the selection of candidates (forced AC and DC line candidates)

2.3 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, when introduced as forced candidate by the user) and line (HVDC only when introduced manually by the user).
- 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.
- 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 pre-processor, initially, was designed and coded to interact with the planning tool in an automated way considering three loops related to three target time horizons. The necessity to reduce the computation time led to a modification of the methodology. However, the main steps of the whole process remain the same:

- The planning tool runs a OPF of the non-expanded grid model plus scenario for the first year.
- The pre-processor proposes a set of candidates using both OPF input and output files.
- The Grid Expansion Problem is run by the planning tool with the grid, scenario and candidates as input.
- The planning tool provides a list of selected candidates that optimize system cost.
- Selected candidates are included in the grid model to create the non-expanded network for the next temporal horizon.

These steps are run three times to consider 2030, 2040 and 2050. In the initial proposal, the final candidates were selected following a joint optimization for the whole period 2030 to 2050. In the final version, this is done in steps, aggregating two decades maximum (2030-2040 and 2040-2050).

The pre-processor provides the planning tool with the cost and technical characteristics of all candidates.. When the user has proposed a line candidate between two nodes that initially are not connected, the pre-processor calls the line routing software tool, which selects the best route and technologies to connect two substations, considering landscape characteristics, existing routes, etc.

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 2.8. The figure also shows the link between the pre-processor and the **line routing tool**, which provides the line characteristics between two substations.

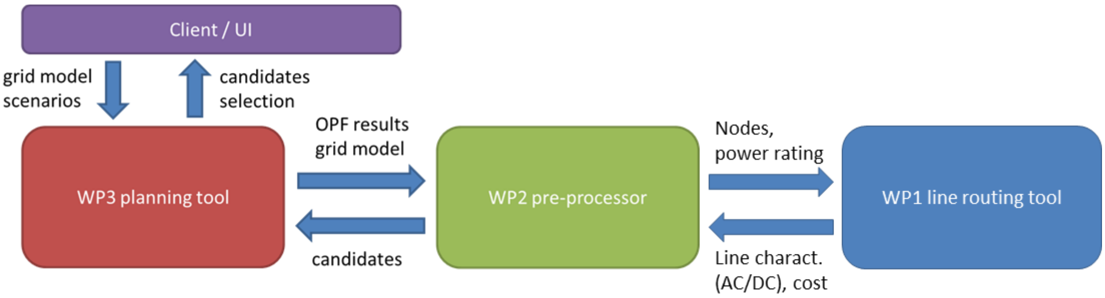

Figure 2.8 – Interaction between planning tool, client and pre-processor

The pre-processor is hosted in a N-SIDE server (cloud) as docker image, and it is accessible through a web API. JSON format files are used to exchange the information with it in accordance with the specifications issued by WP3.

The interaction with the **WP1 tool** that optimizes the routing of a line between two substations has the following characteristics:

- The candidate pre-processor calls the Julia Package containing the tool, which is cloned in the pre-processor.

- This line candidates (between substations not connected previously) are introduced by the user (forced) and, when called by the pre-processor, the WP1 tool provides cost and technology information. Then, the pre-processor takes that output information and completes the rest of the candidate JSON template.
- The new candidates are included in the candidate list by the 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 11-1), 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 are caverns available CAES is 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 caverns prevents the use of CAES systems. 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 hydrogen 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 is installed in transmission/subtransmission network and, in distribution, the line/transformer is substituted. 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).

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, a standard cost is provided per rated power of the line (Annex IV, Table 9-2., this annex provides line and transformer related information). This last approach is also used for transformers (Annex IV, **Errore. L'origine riferimento non è stata trovata.**).

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 are represented in the tables of Annex VIII (section 12), 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 (not in the last version of the planning methodology). 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**:
  - **Input**: OPF input and output files: OptimalPowerFlowInputfile.json and OptimalPowerFlowOutputfile.json
  - **Output:** including output files from the pre-processor to the planning: GridExpansionPlanningInputFile.json.
  - **Debug scenario**: including files that provide additional information for debugging purposes, such as error log, congestion maps, output text files…
- **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).

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.

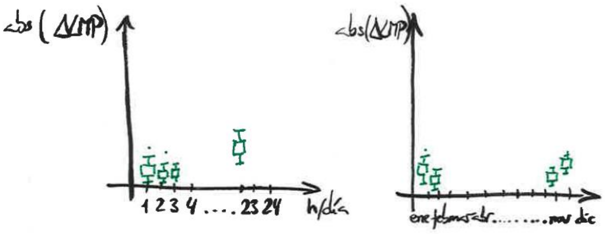

Figure 3.1 – Branches' statistical information graphs (for debugging purposes)

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 (maxNumberOfCandidates, normally from 25 to 100), 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 maximum number of candidates selected from the influence of a congested line (currently, 30% of the maximum number of candidates with a maximum of 5).

4 Preliminary validation tests and results[3]

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[4] 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).

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[3] The validation of the last version of the pre-processor is considered in D2.4. This was the validation at the time when the first version of the deliverable was written but, due to Project requirements, the pre-processor had several adaptations to cope with the evolving requirements.

[4] 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): $\mu_l^{up} - \mu_l^{low}$

- 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 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.

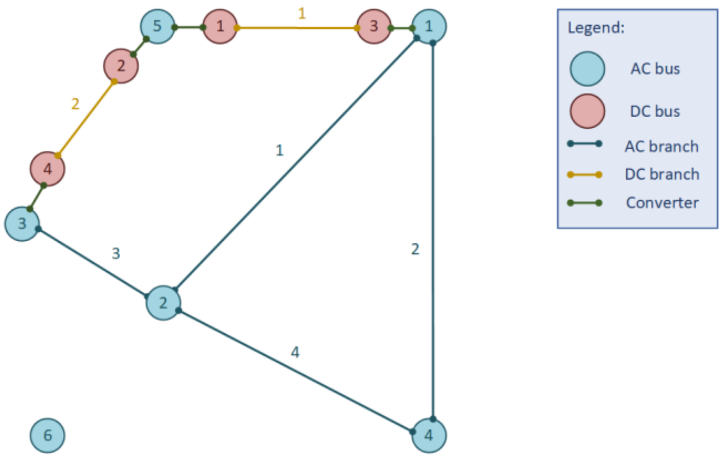

Figure 4.4 –IEEE 6 bus system

- 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.

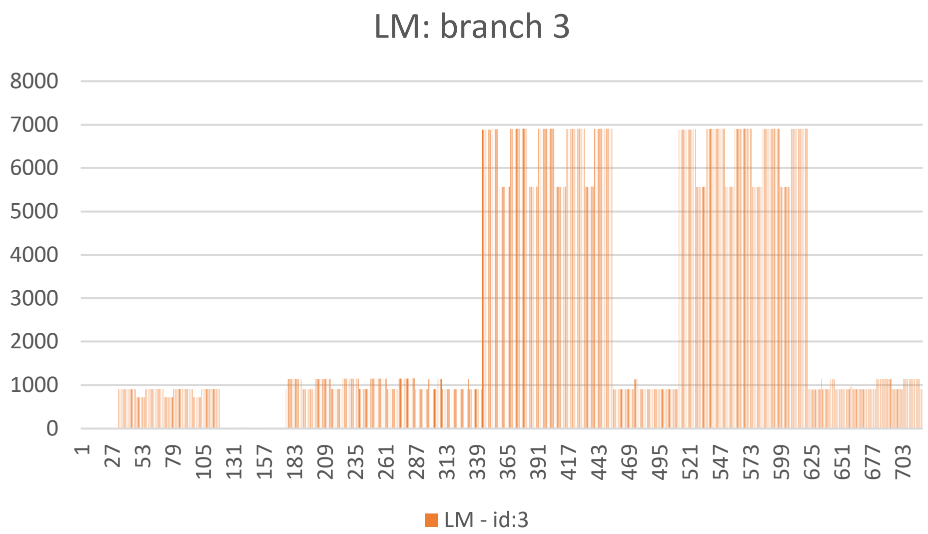

Figure 4.5 – LM values of branch 3 of the IEEE 6 bus system (output from the planning tool)

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.

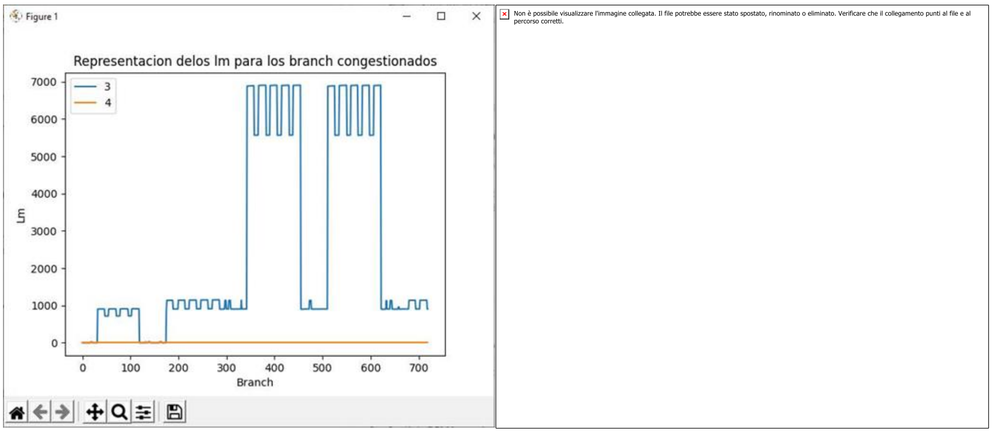

Figure 4.6 – LM values of branch 3 and 4 (left) and statistically (right) as result of the pre-processor

The following figure shows the congested lines in a map.

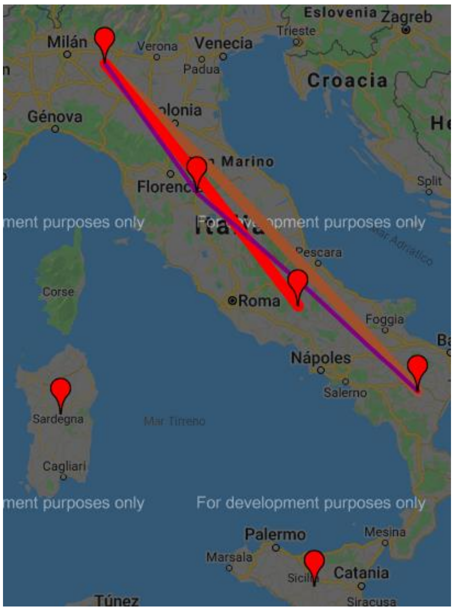

Figure 4.7 – Map showing the congested branches (red and orange)

5 References

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6 Annex I – Locational and congestion constraints

Technology		Bus related characteristics and constraints																
		Type of bus				Resources		Location of bus					Total Restriction (1)	Congestion duration (5)				
		Substation		Load	Power Plant	no water	no cavern	urban	industry	semi-rural	Rural			Hours				Yearly
		air	under								Plain	Mount.		<2	2-6	6-24	>24	>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)													
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) 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*
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
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			Peak Power Demand	Cost (per year)					
	2030	2040	2050		2030		2040		2050	
	kW	kW	kW	MW	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)	CAPEX (€/kW)	OPEX (€/kWh)
Sawmills and Wood Preservation	1799	1799	1799							
Non-metallic Mineral Mining and Quarrying	1000 [5] [6]	1000 [5] [6]	1000 [5] [6]	100 (1%)						
Converted Paper Product Manufacturing	1133	1133	1133	107 (1.1%)						
Cement	1000	1000	1000	105 (1%)						
Fruit and Vegetable Preserving and Specialty Food Manufacturing	881	881	881	55 (1.6%)						
Agriculture, Construction and Mining Machinery Manufacturing	865	865	865							
Basic Chemical Manufacturing	623	623	623	200 (0.3%)						
Other Electrical Equipment and Component Manufacturing	583	583	583		29	17	22	13	15	9
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]	149 (0.2%)						
Support Activities for Crop Production	490	490	490							
Aerospace Product and Parts Manufacturing	472	472	472	159 (0.3%)						
Other Fabricated Metal Product Manufacturing	384	384	384	70 (0.55%)						

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	88 (0.3%)						
Cattle Ranching and Farming	255	255	255							
Beverage Manufacturing	244	244	244	40 (0.6%)						
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]	1 (26%)						
Hospital	300 [6]	300 [6]	300 [6]	7 (4%)						
Supermarket	60 [6]	60 [6]	60 [6]	0.45 (15%)						
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 (big consumers) (when not available for specific load types)	**Standard demand reduction**		
	2030	**2040**	**2050**
	p.u.	**p.u.**	**p.u.**
Big Industrial loads (identified)	0.01 (by default, if class not specified)		
Big Commercial loads (identified)	0.15		

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

Demand Response activities (small consumers in distribution)	Standard demand reduction			Investment cost (to make loads flexible)	
	2030	2040	2050	2030 – 2040 - 2050	2030 – 2040 - 2050
	as % of total load			CAPEX (€/kW)	OPEX (€/kW)
mostly residential	0.5%	2%	5%	0.001 (100€/100MW)	
mostly commercial	15%	15%	15%		
mostly industrial	1%	1%	1%		
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 7-6 – 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).

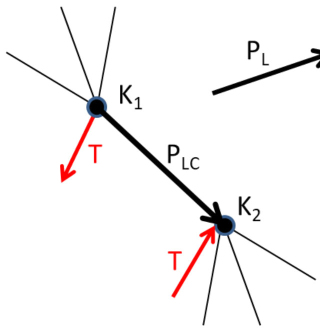

Figure 8.1 – PTDF analysis approach

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:

$$P_l - P_l^0 = T\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right) \tag{2}$$

$$P_{lc} - P_{lc}^{max} = T\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right) \tag{3}$$

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

$$P_{lc} - P_{lc}^{max} = \frac{\left(PTDF_{K_2,lc} - PTDF_{K_1,lc}\right)}{\left(PTDF_{K_2,l} - PTDF_{K_1,l}\right)}\left(P_l - P_l^0\right) \tag{4}$$

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}*.

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

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

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

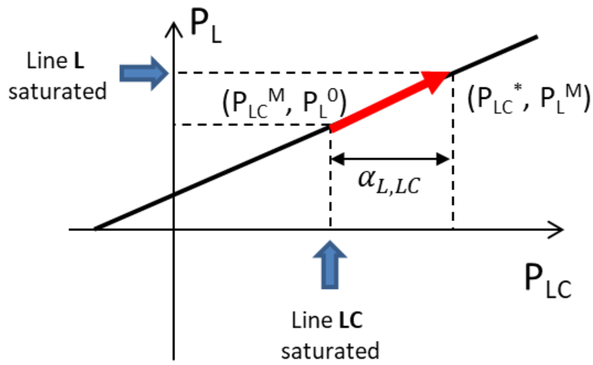

Figure 8.2 – Relationship between the saturation of the congested line and of a line in the influence area

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

This approach have some flaw. In reality, the power injection and extraction buses, K_1 and K_2 in the example, should not be taken arbitrary, since the power flow will take one or other path in the network depending on where both the injection and extraction of power are considered (this can be clearly seen through the PTDF matrix). it is not either correct to take them at the ends of the congested branch. The correct way of facing the problem would be to perform a new OPF with the new restriction (relaxation in 1MW of the rating of the congested line) and see which are the power injection and extraction variations in the system. If no curtailment happens in loads, variations should be seen in generators' dispatch: some would generate more and some less. These generators would define the injection and extraction points (K_1 and K_2) to be considered to check the power flow variation in the lines of the network through the PTDF matrix. However, this approach is not compatible with the FlexPlan methodology and, therefore, the approach mentioned above is considered as simplification.

In addition, the approach is not valid for distribution lines, which are radial. In this case, the value of alfa is very high because the denominator of equation (6) becomes zero.

9 Annex IV – Standard size and costs for conventional assets

Line technology	ID	Size (MW)				
		2030/2040/2050*				
		400 kV	220kV	100-150kV	36-100kV	<36kV
AC overhead	ACOHL	• 1330 MW (two conductors in a bundle) • 1870 MW (three conductors in a bundle) • Approx.: 1300-2000 MW per one system	• Apporx.:350 MW - 480 MW (HTLS conductors)	• 123 MW • 260 MW (150kV, REN) • Approx.: 120-150 MW		• Approx.: 10-20 MW
AC underground (cable)	ACUGC	• Approx.: 1000 MW	• 400 MW • 300 MW	• Approx. 80 –190 MW		

*In principle, no big changes are expected in the next years.

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

Lines	Overhead (€/km)	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	
110-150kV		
45-60kV		
20-30kV	60 000	90 000
		Subsea (€/km)
All cables types		900 000
AC cables		1 100 000
DC cables		750 000

Table 9-2 – Standard cost of lines (Source: ELES, e-distribuzione)

Voltage	Variable Cost (€/km)		Fixed Cost (€)
	1 Circuit	2 Circuits	
0 – 30 kV	60 000	120 000	60 000
30 -70 kV	95 000	190 000	120 000
70- 180 kV	250 000	400 000 (> 600A*)	300 000
180 – 250 kV	350 000	450 000 (> 1 000A*)	500 000
250 kV -	500 000	750 000 (> 2 100A*)	700 000

* Last revision by Terna (not implemented in the code because they arrived later than its final version was issued): 1000 MVA for 380 kV (1520A), 200 MVA for 220 kV (524A) and 130 MVA for 150 kV (500A)

Table 9-3 – Standard cost of lines implemented in the current version of the tool (inputs by Terna for the transmission system)

kV and type	Min X (Ω/km)	Max X (Ω/km)	Avg. X (Ω/km)	Max. length (km)	Avg. length (km)
11-20					
Line	0.403	0.403	0.403	75	9.9
20					
Cable	0.09	0.114	0.102	41	6
30					
Cable	0.096	0.123	0.106	8.6	2.2
Line	0.392	0.392	0.392	34.6	18.7
63					
mixed	0.332	0.332	0.332	119	3
150					
mixed	0.391	0.391	0.391	96	25
220					
mixed	0.338	0.338	0.338	176	23
400					
mixed	0.308	0.308	0.308	245	57

Type	Avg. X (Ω/km)
Cable	0.104
Line	0.398
Mixed	0.342
Total Avg.	0.174

Table 9-4 – AC line average voltage versus impedance characteristics, below summary table (Source: ENTSOE model, Iberdrola line projects)

10 Annex V –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 10-1 –Mean time to repair, failure rate and emergency rating information [12][13][14]

11 Annex VI – 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 Manufacturing	INDLFRVG	
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 11-1 – Bus description codes

12 Annex VII – 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->p.u.)	From pre-processor results			From pre-processor results			From pre-processor results		
selfDischargeRate (p.u. per hour) [8]	2.74 10^{-5}*	2.74 10^{-5}*	2.74 10^{-5}*	0	0	0	0	0	0
minEnergy (MWh->p.u.)	20%	20%	20%	20%	20%	20%	10%	10%	10%
initEnergy (MWh->p.u.)	50%	50%	50%	50%	50%	50%	50%	50%	50%
maxEnergyYear (MWh->p.u.) (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->1/h)	-	-	-	-	-	-	-	-	-
maxInRamp (MW/h->1/h)	-	-	-	-	-	-	-	-	-
maxReactivePowerExchange (MVA->p.u.)	33% of P	33% of P	33% of P	33% of P	33% of P	33% of P	33% of P	33% of P	33% of P
minReactivePowerExchange (MVA->p.u.)	-33% of P	-33% of P	-33% of P	-33% of P	-33% of P	-33% of P	-33% of P	-33% of P	-33% of P
maxAbsActivePower (MW->p.u.)	From pre-processor results			From pre-processor results			From pre-processor results		
maxInjActivePower (MW->p.u.)	equal to max. abs power			equal to max. abs power			equal to max. abs power		
Investment cost (€) ****	From pre-processor results			From pre-processor results			From pre-processor results		
lifetime (years, multiple of 10)	10			10			10		
horizons	From pre-processor (year under study)			From pre-processor (year under study)			From pre-processor (year under study)		
isUnique	True			True			True		
Scenario									
PowerExternalProcess (p.u., time series)	0			0			0		
initEnergy (p.u.)	0.5			0.5			0.5		
finalEnergy (p.u.)	0.5			0.5			0.5		

*2% per month

**FCE: Full Cycle Equivalent

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

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

Table 12-1 –Batteries candidate data model (elaborated from [3] references, where not stated differently)

Data model fields	Hydrogen		
	2030	2040	2050
id	H2_BusConnected		
acBusConnected	From pre-processor results		
maxEnergy (MWh->p.u.)	From pre-processor results		
selfDischargeRate (p.u. per hour) [8]	0	0	0
minEnergy (MWh->p.u.)	0%	0%	0%
initEnergy (MWh->p.u.)	50%	50%	50%
maxEnergyYear (MWh->p.u.) (elaborated from on [9])	4000 hours*	unlimited**	unlimited**
absEfficiency (p.u.)***	0.82***	0.85	0.85
injEfficiency (p.u.)***	0.50***	0.55	0.60
maxAbsRamp (MW/h->1/h)	-	-	-
maxInRamp (MW/h->1/h)	-	-	-
maxReactivePowerExchange (MVA->p.u.)	33% of P	33% of P	33% of P
minReactivePowerExchange (MVA->p.u.)	-33% of P	-33% of P	-33% of P
maxAbsActivePower (MW->p.u.)	From pre-processor results		
maxInjActivePower (MW->p.u.)	equal to max. abs power		
Investment cost (€)	From pre-processor results		
lifetime (years, multiple of 10)	30		
horizons	From pre-processor (year under study)		
isUnique	True		
Scenario			
PowerExternalProcess (p.u., time series)	0		
initEnergy (p.u.)	0.5		
finalEnergy (p.u.)	0.5		

* 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 upper vessel of pumped-hydro storage

Table 12-2 –Hydrogen 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->p.u.)	From pre-processor results			From pre-processor results		
selfDischargeRate (p.u. per hour) [8]	0	0	0	0	0	0
minEnergy (MWh->p.u.)	0%	0%	0%	0%	0%	0%
initEnergy (MWh->p.u.)	50%	50%	50%	50%	50%	50%
maxEnergyYear (MWh->p.u.) (elaborated from on [9])	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
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->1/h)	-	-	-	-	-	-
maxInRamp (MW/h->1/h)	-	-	-	-	-	-
maxReactivePowerExchange (MVA->p.u.)	33% of P	33% of P	33% of P	33% of P	33% of P	33% of P
minReactivePowerExchange (MVA->p.u.)	-33% of P	-33% of P	-33% of P	-33% of P	-33% of P	-33% of P
maxAbsActivePower (MW->p.u.)	From pre-processor results			From pre-processor results		
maxInjActivePower (MW->p.u.)	equal to max. abs power			equal to max. abs power		
Investment cost (€)	From pre-processor results			From pre-processor results		
lifetime (years, multiple of 10)	30			30		
horizons	From pre-processor (year under study)			From pre-processor (year under study)		
isUnique	True			True		
Scenario						
PowerExternalProcess (MWh->p.u., time series)	0			0		
initEnergy (p.u.)	0.5			0.5		
finalEnergy (p.u.)	0.5			0.5		

Table 12-3 –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.)	1 trans. 0.9 dist.	1 trans. 0.9 dist.	1 trans. 0.9 dist.
gracePeriodUDS (h)* (suggested 18-24h)	18	18	18
gracePeriodDDS (h)* (suggested 18-24h)	18	18	18
maxEnergyNotConsumed (p.u.) (suggested 0.1-0.2)	0.1		
curtailmentCost ** (€/MWh -> €/h)	130000		
compensationDemandShift (€/MWh -> €/h)	50 000		
compensationConsumeLess (€/MWh -> €/h)	2 000		
superiorBoundNCP (p.u. Fraction of demand reference)	from Table 7-5, Table 7-6		
superiorBoundUDS (p.u. Fraction of demand reference)	equal to superiorBoundNCP		
superiorBoundDDS (p.u. Fraction of demand reference)	equal to superiorBoundNCP		
valueOfLossLoad** (€/MWh -> €/h)	Same of non-flexible load		
maxEnergyShifted (p.u.)	0.2		
isFlexible	True (flexible load)		
invcost (€) ***	1000		
lifetime (years, multiple of 10)	10		
horizons	True		
isUnique	True		

* UDS: first we increase consumption, later we decrease consumption

DDS: first we reduce consumption, later we increase it

**CurtailmentCost = VoLL = 1.3 €/kWh (for industrial customers) = 1300€/MWh = 130000€/100MWh

***Investment cost: cost for the load to enable flexibility (which can cover the new energy management systems installation, for instance). 1000€

Table 12-4 –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 WP2 pre-processor results (True/False)		
susceptance (p.u.)	Similar to existing or from WP1		
resistance (p.u.)	Similar to existing or from WP1		
reactance (p.u.)	Similar to existing or from WP1		
voltageTapRatio (p.u.)	1 (for both lines and transformers)		
maxAngleDifference (rad)	2π		
minAngleDifference (rad)	-2π		
meantimeToRepair (h)	From table Table 10-1		
failureRate (1/year)	From table Table 10-1		
emergencyRating (p.u.)	From table Table 10-1		
ratedApparentPower (p.u.)	From WP1 line routing tool		
IsInterconnection	True/False		
length (km)	Similar to existing or calculated from Table 9-4		
InvestmentCost (€)	From * Last revision by Terna (not implemented in the code because they arrived later than its final version was issued): 1000 MVA for 380 kV (1520A), 200 MVA for 220 kV (524A) and 130 MVA for 150 kV (500A) **Table *9-3***		
lifetime (years, multiple of 10)	50		
horizons	From pre-processor (year under study)		
isUnique	True		

Table 12-5 –AC Branches and transformers data model