

# e-HIGHWAY 2050

## Modular Development Plan of the Pan-European Transmission System 2050

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D8.3.b	Prototype for the definition of optimal grid architectures for 2050		



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## Document information

### General purpose

This document is the deliverable D8.3.b of the e-Highway2050 project. It contains the description of the prototype developed in the framework of task 8.3, named “*Enhanced methodology to define optimal grid architectures for 2050*”.

### Change status

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## EXECUTIVE SUMMARY

This document is the deliverable D8.3.b of the e-Highway2050 project. It contains the description of the prototype developed in the framework of task 8.3, named “Enhanced methodology to define optimal grid architectures for 2050”.

The developed methodology is implemented in four modules:

- A reduction of the initial European network (around 8,000 nodes) to a 1,000-node system, called nodal grid.
- A detection of overload problems (DCOPF model), which quantifies the congestion of transmission lines in the initial nodal grid while using system flexibility in the most efficient way. A mapping of generation and consumption, which disaggregates the hourly time series of load and generation calculated by task 8.2 (adequacy without grid) on each node of the nodal network is performed before running the DCOPFs.
- A reduction of the nodal grid according to critical branches, which calculates an equivalent zonal network (around 100 zones).
- A grid expansion at the nodal level, which starts from the zonal modular development plan calculated in task 8.4 and defines the optimal nodal reinforcements for the first two time horizons. This module is separated from the previous ones by the zonal Transmission Expansion Planning (task 8.4).

The prototype has been implemented using Matlab, AMPL and R languages. The module on grid expansion at the nodal level is performed using TEPES (Transmission Expansion Planning for an Electrical System), a model developed by Comillas.

The method built in the framework of this task is discussed in deliverable D.8.3.a, “Enhanced methodology to define optimal grid architectures for 2050”. The present document describes the prototype developed to carry out this work.

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# 1. Introduction

## 1.1. High level functional description

The prototype implemented in task 8.3 has two main functions: it detects overload problems in the initial nodal network over all time horizons and scenarios in order to build an equivalent zonal model of the grid, and it performs the optimal nodal expansion plan from the obtained zonal modular development plans in task 8.4 for the first two time horizons. Thus, we will present each function separately.

First, the full European grid needs to be reduced up to 1,000 nodes in order to be able to detect overload problems over every Monte-Carlo year of each scenario and time horizon. Moreover, considering the long-term time horizon, it would not be relevant to complete the full network. Once the initial network has been reduced, the hourly injections (generation and consumption) calculated during adequacy simulations (task 8.2) are disaggregated on each node of the simplified nodal grid. Then, hourly DCOPFs are run in order to quantify the congestion of transmission lines in the initial grid, while using system flexibility in the most efficient way. Flexibility can be brought by costless devices (Phase-Shifting Transformers (PST) or HVDC links), or associated to a cost such as redispatching. Finally, the network is once again reduced (100 zones), so that branches identified as critical are kept in the equivalent zonal grid.

The zonal grid model is used to calculate the optimal modular development plan from today to 2050 (task 8.4). This expansion at zonal level gives a solution in the form of grid reinforcements between zones for each scenario and time horizon. Thus, a specification of the optimal nodal expansion plan for the first two time horizons, for which there is a common zonal expansion plan for all scenarios, is performed.

The method built in the framework of the project is discussed in deliverable D.8.3.a, “Enhanced methodology to define optimal grid architectures for 2050”. The present document describes the prototype developed to carry out this work.

## 1.2. Modules developed

The architecture of the developed tool is presented in Figure 1. Only the blue modules are described in this deliverable (modules related to task 8.3).

- In a first module, the full initial network is reduced, so that only very high voltage nodes (400kV nodes) are kept and nodes which are electrically close are assigned together. This first reduction aims at simplifying the initial network to an equivalent nodal grid with around 1000 nodes.
- The second module is divided in two steps. First, hourly times series of consumption and generation calculated by the adequacy module (see D8.2.b for the tool description) are disaggregated on each node of the simplified nodal grid for each horizon, scenario and Monte-Carlo year. This is done according to distribution keys (input data). Then, hourly DC Optimal Power Flows (DCOPF) detect network congestions for each horizon, scenario and Monte-Carlo year.
- In the following module, the simplified nodal grid obtained by the first module is reduced to an equivalent zonal network with around 100 zones. This network reduction has the particularity of defining critical lines using indicators calculated in the DCOPFs, and keeping these selected branches in the reduced grid.
- Finally, a nodal development plan for the first horizons is developed taking into account the optimal zonal modular development plan calculated in task 8.4 (see D8.4.b for the prototype description).

This module uses TEPES (Transmission Expansion Planning for an Electrical System), a model developed by Comillas.

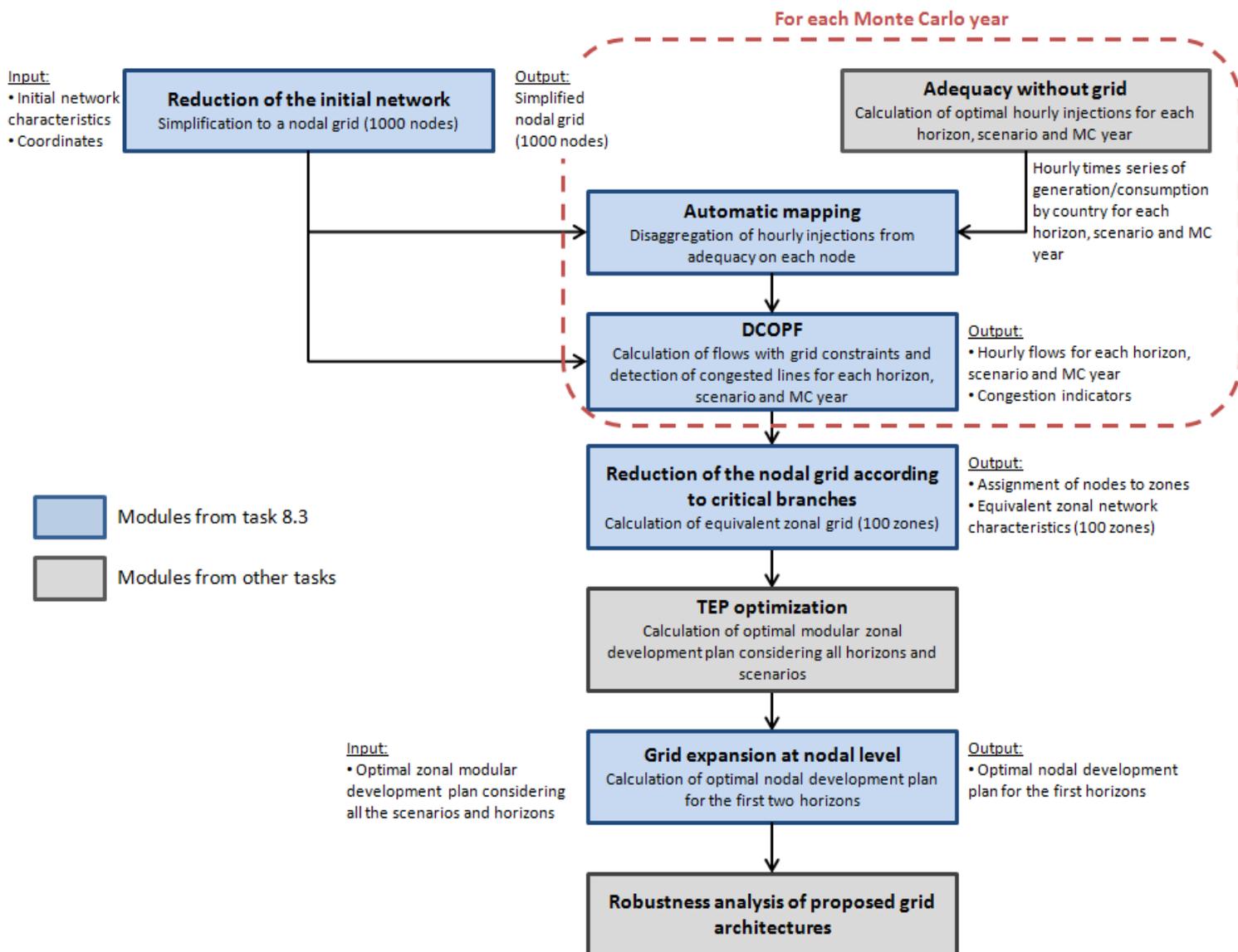


Figure 1. Architecture of the developed tool

A Monte-Carlo approach has been retained to take into account the stochasticity of the problem and to study the response of the power system to diverse possible events. Consequently, the first modules (circled in red in Figure 1) are repeated numerous times; they can even be parallelized.

### 1.3. Implementation

The delivered scripts should be run on a Linux environment. CentOS release 6.5 was installed on the machine used for tests.

Four languages were used to implement the methodology: Matlab, AMPL, R and Bash.

Both network reduction modules presented above have been prototyped with Matlab.

The DCOPF module integrates optimisation problems and has been prototyped with AMPL. The automatic mapping module has been implemented with AMPL too. Indeed, it is more suitable for data handling as it fits between two optimisation modules using AMPL (adequacy without grid and DCOPF).

An R script is used to process large amount of data from the hourly DCOPFs.

The last module is referred to the grid expansion at nodal level. This expansion at the nodal level is performed using the TEPES model, which is developed using GAMS.

All the modules are controlled with Bash scripts, as they are used in a single method.

## 2. Data organisation

The methodology of WP8 involves different scenarios, time horizons and Monte-Carlo years and therefore necessitates handling large volumes of data. Thus, each data relative to a specific scenario, horizon or Monte-Carlo year is organized as presented in Figure 2:

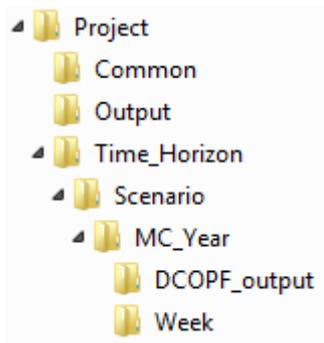


Figure 2. General folder architecture

The data generated by the adequacy simulations is stored as weekly files of hourly injections of load and generation in the corresponding folder ( $\$Time\_Horizon/\$Scenario/\$MC\_Year/\$Week$ ). These files are “space separated” text files, and are the input data of the DCOPF module, once they have been disaggregated on each node of the simplified nodal grid. The outputs from the DCOPFs (power flows, adjusted nodal injections, marginal costs...) are stored annually, and not weekly, in “semi-colon separated” csv files in each “DCOPF\_output” folder. These files are used as inputs for the network reduction module, which defines critical branches from the indicators calculated in the DCOPFs. Weekly files from the adequacy simulations are also used by the nodal expansion module, but only for a subset of snapshots.

Both reduced networks are common data for all scenarios, horizons and Monte-Carlo years. Thus, they are stored in a common folder located at the root, called “Common”. This is the same for any other common data or script. The common outputs, such as the nodal development plan, are stored in the “Output” folder at the root.

The whole methodology is performed thanks to the “main.sh” script. The numbers of horizons, scenarios and Monte-Carlo years to run are defined in this script. Then, it executes all the modules successively, except for the adequacy module (see D8.2.b), the automatic mapping and the DCOPF modules, which are run in parallel for each year. Indeed, each Monte-Carlo run is independent from the others.

The next sections describe each module developed for task 8.3.

## 3. Reduction of the initial network

### 3.1. Objective

The goal of this module is to reduce the full initial European HV network ( $\approx 8,000$  nodes) to a simpler nodal grid with around 1,000 nodes, by only considering electrical distances.

Thus, the main inputs of this module are the description of the initial network. There is one file for each element of the grid:

- **network\_substations.txt** contains the description of each substation (voltage level, country, name,...). It is important to note that we do not consider the topology of the network in the WP8 methodology, as we are looking at long term horizons. Thus, a substation is equivalent to a node in our model.
- **network\_branches.txt** contains the description of each branch. Each transmission line is defined by two end nodes, which are listed in the “network\_substations.txt” file. The electrical characteristics of the branch (reactance, resistance, susceptance,...), its thermal capacity or the number of the corresponding Phase-Shifter Transformer (PST) if there is one, are indicated as well. AC and DC transmission lines are both described in the same file.
- **network\_ptc.txt** and **network\_tct.txt** describe each PST of the network, with its corresponding table.

The data contained in these files allow us to calculate the electrical distance between each pair of nodes, and to cluster the nodes which are electrically close. However, only nodes with the highest voltage level (400kV) are considered in the partition phase to avoid distorting the electrical distance (see D8.3.a). The remaining lower voltage nodes are assigned according to geographical distances. Thus, nodes coordinates are also needed as inputs (**network\_coordinates.csv**).

The following figure shows the inputs and outputs for the initial network reduction.

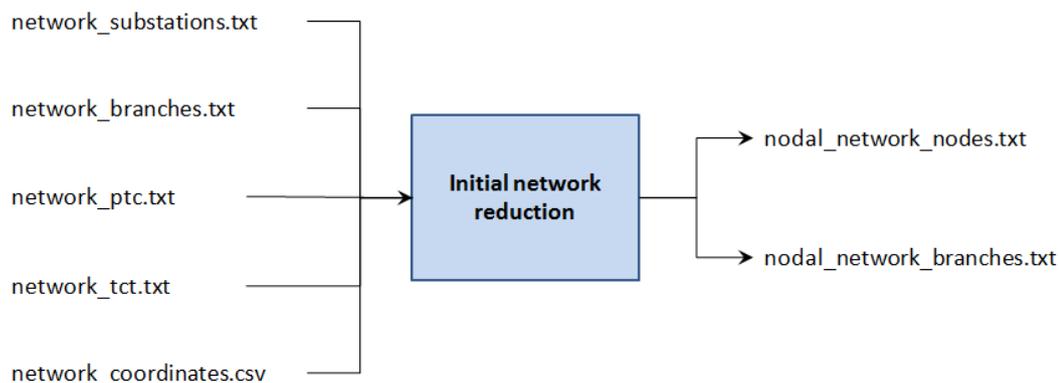


Figure 3. Input/output diagram for the initial network reduction module

This module has been implemented in Matlab, and the main script is **initial\_reduction.m**.

### 3.2. Description of outputs

The outputs illustrated in Figure 3 are described below:

- **nodal\_network\_nodes.txt** contains all the nodes kept in the reduction (representative node of each partition). They all have the same voltage level (400kV), as only nodes with the highest voltage

level are considered in the partition. Each node from the simplified nodal network is described by its coordinates (from “network\_coordinates.csv”) and its country. This data is the minimum required by the following modules.

- **nodal\_network\_branches.txt** contains the description of the equivalent branches calculated by the reduction module. Each branch of the simplified nodal grid is defined by its two end nodes, its electrical characteristics (reactance, resistance, susceptance,...), its capacity, its type (AC or DC) and its corresponding PST number if there is one.

Another output can be provided by this script, which gives the correspondence between nodes from the initial network and nodes from the simplified nodal grid. This information will not be used in the following tasks, as the simplified nodal grid is the most detailed grid modelling used in the methodology. However, it can be used to monitor the clustering results from this module.

Once the simplified nodal network has been built, there is no need to run the script again if the initial network data does not change. This network model is the same for all the scenarios and all the time horizons.

## 4. Detection of overload problems

### 4.1. Objective

The goal of this module is to detect overload problems on the simplified nodal grid considering all the scenarios, horizons and Monte-Carlo years. This is done by running hourly DCOPFs which aim at minimizing the cost of adjusting controllable injections from the optimal dispatch, while complying with grid constraints and using possible network controls (PST, HVDC). The hourly optimal injections are calculated by adequacy simulations in copperplate at the country level. Before running the DCOPFs, the hourly injections from adequacy simulations need to be disaggregated on each node of the simplified nodal network, obtained by the previous module. Thus, this module is split in two steps:

- **Automatic mapping:** Disaggregate hourly time series of generation and consumption from adequacy simulations on each node of the simplified nodal grid, according to distribution keys. These keys are an input of the methodology and they depend on the scenario and time horizon.
- **DCOPF:** Hourly DC Optimal Power Flow, which quantifies the congestion of transmission lines in the initial grid, while using system flexibility in the most efficient way. Flexibility can be brought by costless devices (Phase-Shifting Transformers (PST) or HVDC links), or associated to a cost such as redispatching.

The following figure shows the inputs and outputs for mapping of injections.

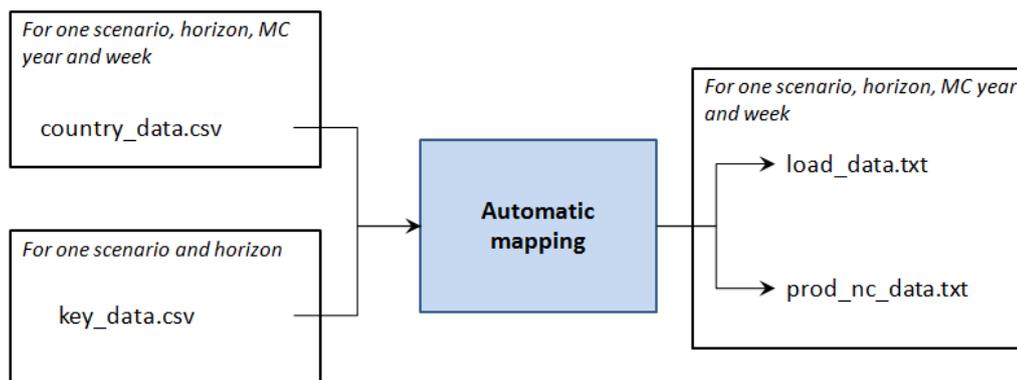


Figure 4. Input/output diagram for the automatic mapping of injections

This step is run following an adequacy simulation. Each adequacy simulation is done over a week (see D8.2.a), this is why the input data file with injections (**country\_data.csv**) only contains hourly injections for one week. The disaggregated injections are uncontrollable generation (wind, solar, hydro run-of-river) and load.

Figure 5 illustrates the inputs and outputs for DCOPFs. Each DCOPF is run over one hour. Thus, this process is repeated several times. The input data are the hourly system cost (**cost\_data.txt**) and the hourly nodal injections (generation and consumption, **prod\_data.txt** and **load\_data.txt**) calculated in the adequacy simulations and disaggregated in the previous step. The simplified nodal grid description is also considered to build the constraints of the optimization problem:

- **nodal\_network\_nodes.txt** and **nodal\_network\_branches.txt** are the outputs from the initial network reduction module,
- **network\_ptc.txt** and **network\_tct.txt** describe the PST in the initial network (the indexes are the same in the simplified network).

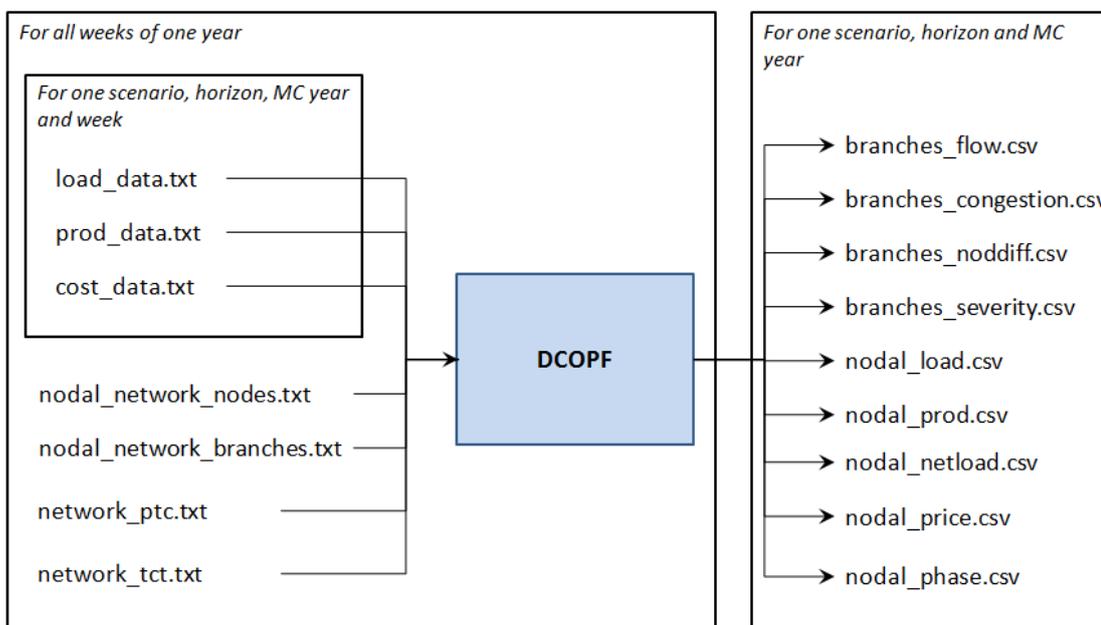


Figure 5. Input/output diagram for the DCOPFs over one year

## 4.2. Description of outputs

The outputs from the automatic mapping module are described below:

- **load\_data.txt** contains the hourly nodal injections of load from the optimal dispatch (adequacy without grid).
- **prod\_nc\_data.txt** contains the hourly nodal injections of non controllable generation (wind, solar, hydro run-of-river) from the optimal dispatch.

These files are generated for each week of all Monte-Carlo years, horizons and scenarios.

The outputs from the DCOPFs are indicators that will be used in the following network reduction module, in order to define critical branches for the system and calculate the equivalent network characteristics. There is one file per indicator and Monte-Carlo year, and each indicator is defined for every line and node:

- **branches\_flow.csv** contains the hourly flows over every line of the network, calculated in the DCOPF. They are relative flows, which mean that they have been divided by the line capacity.
- **branches\_congestion.csv** indicates the proportion of time within the year where the line is congested. This indicator is calculated for each branch.
- **branches\_noddiff.csv** contains the hourly indicators, defined as the difference between the nodal prices at the extremes of the line weighted with the line flow. This indicator is calculated for each branch.
- **branches\_severity.csv** contains the hourly values of the dual variable of the capacity limit constraints considered when solving the DCOPF for each line.
- **nodal\_load.csv** contains the hourly nodal injections of load, adjusted by the DCOPF from the optimal dispatch.
- **nodal\_prod.csv** contains the hourly nodal injections of generation, adjusted by the DCOPF from the optimal dispatch. All types of generation are summed on each node, so that there is one injection per node.
- **nodal\_netload.csv** contains the hourly nodal injections of net load, defined as the difference between load and non controllable generation (wind, solar, hydro run-of-river).
- **nodal\_price.csv** contains the hourly nodal prices, that is the dual variable of the balance constraints considered when solving the DCOPF.
- **nodal\_phase.csv** contains the hourly nodal voltage angles, calculated in the DCOPF.

Once these hourly values have been computed for each scenario, time horizon and Monte-Carlo year, they are processed with a script, which calculates the mean value of each indicator over all scenarios and horizons for every line and node. Deciles of some indicators over all scenarios and horizons are also calculated. The final outputs of this module are described below:

- **ind\_flow.csv** contains the mean values and deciles of the flows over all scenarios and time horizons, calculated for each line.
- **ind\_congestion.csv** contains the mean values of the proportion of time where the lines are congested over all scenarios and time horizons, calculated for each line.
- **ind\_noddiff.csv** contains the mean values and deciles of the indicator related to the nodal price differences, calculated for each line, over all scenarios and time horizons.
- **ind\_severity.csv** contains the mean values and deciles of the severity indicator, calculated for each line, over all scenarios and time horizons.
- **ind\_load.csv** contains the mean values of nodal load injections over all scenarios and time horizons.
- **ind\_prod.csv** contains the mean values of nodal generation injections over all scenarios and time horizons.
- **ind\_nodprice.csv** contains the mean values and deciles of nodal prices over all scenarios and time horizons.

- **ind\_phase.csv** contains the mean values of nodal voltage angles over all scenarios and time horizons.

These files are common to all scenarios and horizons.

## 5. Reduction of the nodal initial grid according to critical branches

### 5.1. Objective

The objective of this module is to reduce the initial nodal network (around 1,000 nodes) obtained after reduction in Section 3, to a zonal equivalent grid, of about 100 zones, and obtain the equivalent characteristics of this reduced network. This reduced network will be the starting point to perform the transmission expansion at a zonal level.

The obtained reduced network should approximate the behaviour of the power system that drives the transmission expansion as accurate as possible. Therefore, the inter-zonal flows in the reduced system should approximate the inter-zonal flows in the nodal system. And, for this purpose, we define critical branches as the transmission lines that may have a special interest for the transmission expansion planning. Contrary to what has been done before, we now define the zones of the reduced system using these critical branches, and not only the electrical distances.

Once we have obtained the zones in the reduced network, we have to compute the equivalent parameters (reactance and capacity) that describe the corridors among them. Hence, the main inputs for this module are the description of the network provided in the reduction of the initial grid module and the indicators provided in detection of overload problems module to compute the critical branches. In order to compute the equivalent parameters of the corridors, we need also to use the the mean values of nodal voltage angles, nodal injections, flows and several snapshots to compute the capacities of these corridors. Therefore, all the nodal and power flow data related to these snapshots are also an input:

- **nodal\_network\_nodes.txt** and **nodal\_network\_branches.txt** are the outputs of the reduction of the initial network module and contains the network data,
- **ind\_phase.csv**, **ind\_load.csv**, **ind\_prod.csv**, **ind\_flow.csv**, **ind\_congestion.csv**, **ind\_noddiff.csv**, **ind\_severity.csv** are the mean values obtained as outputs in the detection of overload problems module,
- **snapshotbuses.csv** contains the description of each selected snapshot regarding node data: load, generation and net load.

The main inputs and outputs of this module are illustrated in Figure 6.

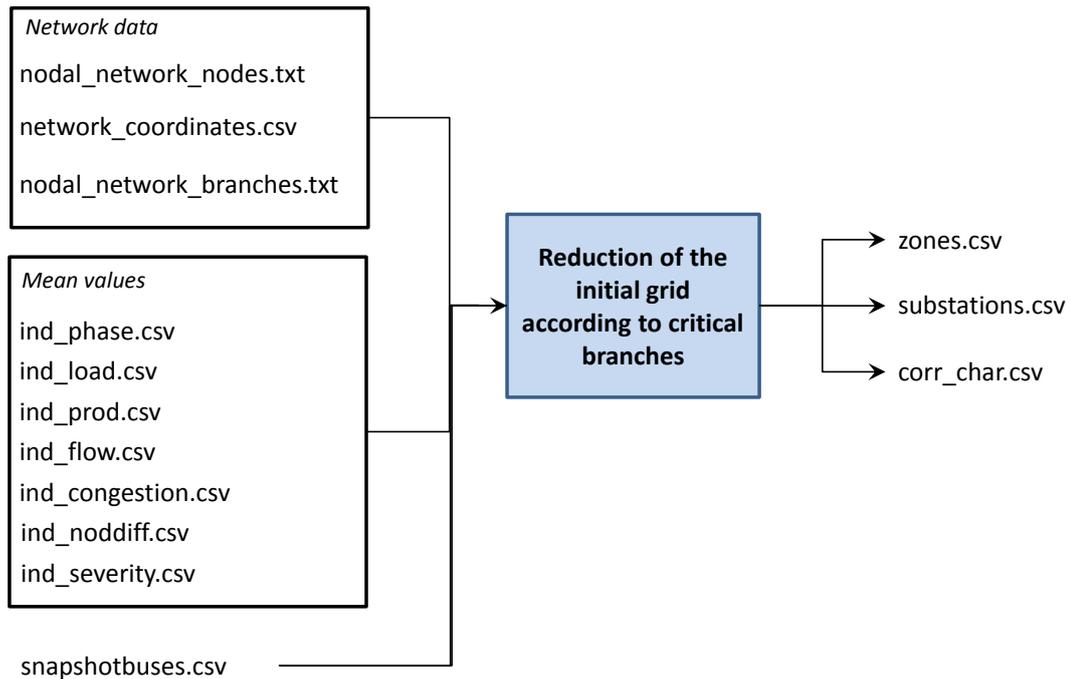


Figure 6. Input/output diagram for reduction of the initial grid according to critical branches

## 5.2. Description of outputs

The outputs provided by this module are described below:

- **zones.csv** contains the zones of the reduced network and its representative node in the initial network.
- **substations.csv** contains the number of each substation in the initial network and the zone where it belongs to.
- **corr\_char.csv** contains the equivalent parameters of the corridors that connect the different zones of the reduced network: connected zones, type (AC or DC), equivalent physical capacity, equivalent reactance and if it is a PST or not.

# 6. Grid expansion at nodal level

## 6.1. Objective

The objective of this module is to perform the transmission expansion planning of the nodal network based on the results provided by the transmission expansion at the zonal level. The expansion at the zonal level will provide a solution in the form of equivalent physical capacities and reactances between zones for each scenario and time horizon. But this is not a directly implementable expansion plan, which needs specific transmission lines with their corresponding end nodes, voltage levels and cable types. Hence, the purpose of this module is to obtain the nodal plan for the two first time horizons, for which there is a common zonal expansion plan for all scenarios.

The transmission expansion planning at the nodal level will be performed using the TEPES model, developed by Comillas<sup>1</sup>.

The main inputs for this module are the description of the network provided in the reduction of the initial grid module, the results obtained in the zonal expansion and the snapshots selected to perform this zonal expansion:

- **nodal\_network\_nodes.txt** and **nodal\_network\_branches.txt** are the outputs of the reduction of the initial network module and contains the network data,
- **snapshots.txt** is an output of the snapshot selection module and contains the list of snapshots selected to perform the transmission expansion at zonal level, with their related time horizon, scenario and weight,
- **prod\_data.txt**, **load\_data.txt** and **cost\_data.txt** which are the hourly nodal injections (generation and consumption) and hourly system cost from the adequacy simulations and disaggregated on the simplified nodal network. Only injections and system costs for the selected snapshots are used in this module. The file prod\_data.txt also contains the cost<sup>2</sup> of generating units.
- **optimal\_increment.csv** is the output of the TEP optimization at zonal level, giving the expansion solution for each candidate in each scenario and time horizon.

The main inputs and outputs of this module are illustrated in Figure 7.

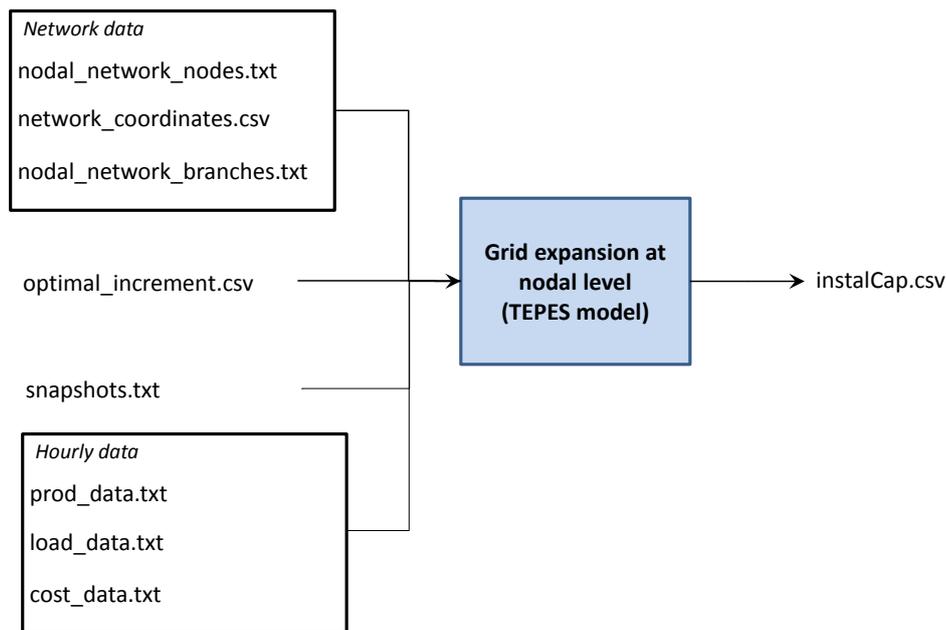


Figure 7. Input/output diagram for reduction of the grid expansion at nodal level

## 6.2. Description of outputs

The outputs provided by this module are described below:

- **instalCap.csv** contains the capacity installed of the different network elements among the nodes of the power system.

<sup>1</sup> More information about the TEPES model can be found in Deliverable D8.3a.

<sup>2</sup> The costs considered are not real costs; they aim at representing the cost of adjusting generation (up and down) and model the priority order between these generation units.

## 7. Conclusion

The four main modules of the methodology of task 8.3 have been implemented using Matlab, AMPL, R and Bash. An organised folder hierarchy has been built in order to manipulate the large volume of data of the different scenarios, time horizons and Monte-Carlo years. Moreover, scripts have been written in order to automate the simulations of several Monte-Carlo years, and run the successive modules automatically.

Some modules may be run in parallel, such as the detection of overload problems; tests were made on a server with 16 CPUs and up to 16 yearly Monte-Carlo simulations were successfully run in parallel.