MOBILE ENERGY RESOURCES

IN GRIDS OF ELECTRICITY

ACRONYM: MERGE

GRANT AGREEMENT: 241399

WP 2
TASK 2.6
DELIVERABLE D2.4

FUNCTIONAL SPECIFICATION FOR ESTIMATING ADDITIONAL INVESTMENTS IN DISTRIBUTION NETWORKS WITH HIGH PENETRATION OF ELECTRIC VEHICLES

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SUMMARY

The MERGE project will perform a throughout assessment of the behaviour of electric power systems with a large penetration of electric vehicles (EVs). Management and control strategies as well as regulatory frameworks for the appropriate integration of EVs will be developed. Several software tools will be used for these purposes.

WP2 of the MERGE project deals with the adaptation and enhancement of the existing tools that are required to address the integration of EVs into electric power systems. These tools all together will form an evaluation suite needed to achieve the objective of the project.

Deliverable 2.4 presents the work done within Task 2.6 "*Estimation of additional investment cost in the distribution networks with high penetration of electric plug-in vehicles".* In this task, two distribution planning models developed by the (Institute for Research in Technology) IIT of Comillas University have been updated so as to allow for the evaluation the need for investments and grid reinforcements due to the introduction of EVs. These models are generically referred to as reference network models (RNMs), being one of them a greenfield RNM and the other a expansion-planning RNM. RNMs must be able to measure the impact of the introduction of EV on system losses and quality of service.

This document describes the functionalities of RNMs as well as their inputs, outputs and internal algorithms. It is shown that a greenfield RNM can design a quasi optimal distribution network from scratch for very large distribution areas given the transmission substations and the end-consumers and other network users such as distributed generators (DG) or EVs. Similarly, the expansion-planning RNM can design a reference network but starting from a given initial grid which can either correspond to the actual network or a reference network obtained with the greenfield RNM. RNMs consider both technical constraints (voltage limits, thermal capacity, etc.) and geographical constraints (forbidden regions, street maps and orography). As a result, the RNMs provide all the technical and economic information of the network obtained as well as the energy losses incurred broken down per voltage levels.

Finally, the modifications performed in order to measure the impact of EVs on distribution investments and operational issues have been detailed. Traditionally, distribution networks were designed according to the peak demand. However, the future large penetration of EVs and DG will require grid planners to consider a wider range of possible situations, such as peak local generation. Similarly, distribution planning models ought to be adapted. Following this line, the RNMs have been upgraded so as to allow them to design reference networks for very large areas considering several scenarios. Thanks to this modification, the impact of different battery charging strategies throughout the day on distribution networks can now be assessed more precisely.

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ACRONYMS

BEV	Battery Electric Vehicle
DG	Distributed Generation
DSO	Distribution System Operator
EV	Electric Vehicle
GIS	Geographical Information System
HV	High Voltage (typically between 45kV and 150kV)
LV	Low Voltage (230 V, 400 V)
MV	Medium Voltage (usually from 3kV to 30kV)
PHEV	Plug-in Hybrid Electric Vehicle
RD	Royal Decree
RNM	Reference Network Model
WACC	Weighted Average Cost of Capital
WP	Work Package

1 INTRODUCTION

This report presents the work carried out within Task 2.6 belonging to WP2 of the MERGE project. The main objective of WP2 is to develop a set of software tools capable of analysing the consequences of the integration of EVs into electric power systems. More specifically, Task 2.6 consists of adapting existing long-term planning models for electricity distribution networks in order to cope with a high penetration of EVs. These models are known as Reference Network Models (RNMs). This will allow project partners to estimate the additional investments that are required in distribution networks to cope with large amounts of EVs.

In addition to investment costs, the models developed will be able to measure the impacts of EVs on short-term operation aspects such as fixed and variable energy losses and quality of service and translate these into monetary terms. The models will be applied to actual distribution networks taking into account a geographically specific characterisation of local generation and demand.

The remainder of this report is organised as follows. Section 2 will provide a detailed description of the RNMs, including inputs, outputs, and internal architecture and algorithms. Section 3 will detail the modifications that have been performed on the RNMs in order to enhance the analysis of the impacts of EVs.

2 REFERENCE NETWORK MODELS

This section provides an overview of the functionalities of RNMs and a more detailed description of the architecture and algorithms used by the models as well as the necessary inputs and the outputs obtained from the models. The RNMs described in this report have been developed by the Institute for Research in Technology of Comillas Pontifical University in Madrid.

Functionalities of RNMs

RNMs are optimization models able to design an electrical reference or adapted network for very large distribution areas comprising up to a few million consumers. A reference network is a theoretical network that complies with the same geographical, reliability and technical constraints as the actual grid at a minimum cost. Reference networks can be used by regulators as a benchmark for actual distribution networks in order to set the allowed revenues of distribution system operators (DSOs). Spain is one of the pioneers in the application of RNMs to regulate DSOs. The general principles concerning the economic regulation of electricity distribution in Spain using RNMs are set in RD 222/2008 [1].

Broadly speaking, there are two different approaches to obtain a reference network: i) greenfield models and ii) expansion planning models. The former approach builds an optimal network from scratch, hence disregarding historic evolution of the networks. The latter approach takes the current network as the starting point and then builds the reinforcements necessary to cope with both horizontal (new network users) and vertical (changes in load demands and/or generation capacities of existing users) growths in demand and DG production. Furthermore, the initial network considered by the expansion-planning RNM can be obtained by the greenfield RNM, thus allowing us to feed one the models with the results of the other one. This capability has been essential in previous analyses aiming at assessing the impact that DG can have on distribution network costs [2] and to evaluate how the implementation of more active grid operational strategies can mitigate this impact [3].

Distribution network planning with RNMs

As it can be seen in,Figure 1, distribution networks comprise several layers or voltage levels. Distribution grids start at the transmission substations, from where the HV subtransmission networks feed electricity to the distribution substations and HV consumers, typically large industries. Then, the MV grid supplies medium and small industries and commercial consumers as well as the MV/LV transformers. Finally, the LV grid feeds the smallest consumers that comprise small commercial and residential consumers. Subtransmission networks are highly meshed. MV grids are normally built with a certain degree of meshing, particularly in urban areas, although they are operated radially. Finally, LV networks are usually totally radial. As one approaches lower voltage levels, the number of elements grows exponentially. This is one of the main differences as compared to transmission networks.

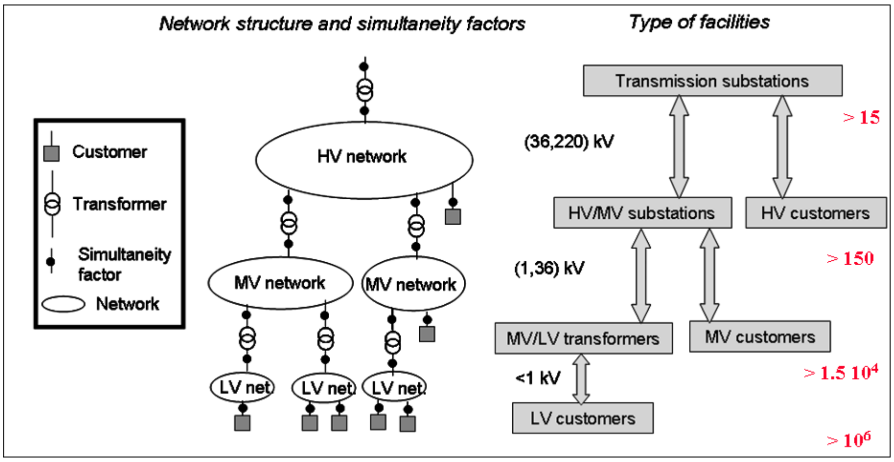

Figure 1: Distribution network structure and simultaneity factors

Figure 1 shows the location of simultaneity factors on different points of the distribution network. Simultaneity factors are needed for planning purposes in order to account for the fact that the maximum power flow in the different network components does not occur at the same moment in time. Without them, network components may be assigned a much bigger size than necessary. For example, if DSOs assumed that all LV consumers consume their maximum power at the same time, LV grids and MV/LV transformers would be much bigger in terms of capacity than what it would be really required. Similarly, MV/LV transformers and distribution substations have two different simultaneity factors, one upstream of the transformer and another one downstream of it. The upstream simultaneity factor models the fact that not all transformers are at their peak at the same time, whereas the downstream one accounts for the fact that not all the lines connected to them will be loaded at their maximum simultaneously.

Simultaneity factors	Typical values
LV customers	0.2 – 0.4
LV feeders	0.8
MV/LV transformers & MV customers	0.8
MV feeders	0.85
HV/MV substations & HV customers	1

Table 1: Typical values for simultaneity factors in Spain

Table 1 provides typical values for simultaneity factors in the Spanish distribution networks. It can be observed that the values of the simultaneity factors increase with the voltage level. This is due to the fact that the higher the voltage level, the lower the number of network users and installations that are aggregated to compute peak flows. It will be explained below how the algorithms take into account the effects of simultaneity factors. Further information can be found in [4].

It is noteworthy that the distribution network is built taking into account the actual location of network users and network components (in the case of the expansion-planning RNM), as well as other geographical constraints such as forbidden ways-through or street maps within urban areas. This is possible owing to the interaction between the planning algorithms and a geographical information system (GIS). Figure 2 shows that the planning algorithms interact with the GIS in order to include the costs increases caused by the geography and topography and to optimise the network layout.

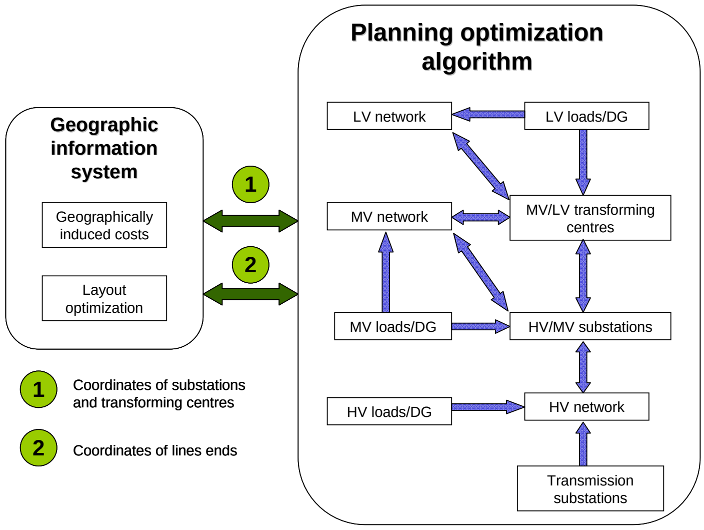

Figure 2: Interaction between the planning algorithms and the GIS

In urban areas, actual distribution networks must be built following the streets since they cannot cross buildings or parks. If necessary, electrical lines may cross the streets, mainly in large avenues perpendicularly to the road. RNMs mimic this behaviour by building an approximate street map based on the location of electricity consumers. Both the urban regions and the street maps are endogenously detected and generated based on the number and density of consumers. Lines are forced to follow these street maps as shown in Figure 3, where blue triangles represent the HV/MV substations and yellow squares the MV/LV transformers. Thick black lines represent the MV feeders and thin green lines correspond to the approximate street map automatically generated.

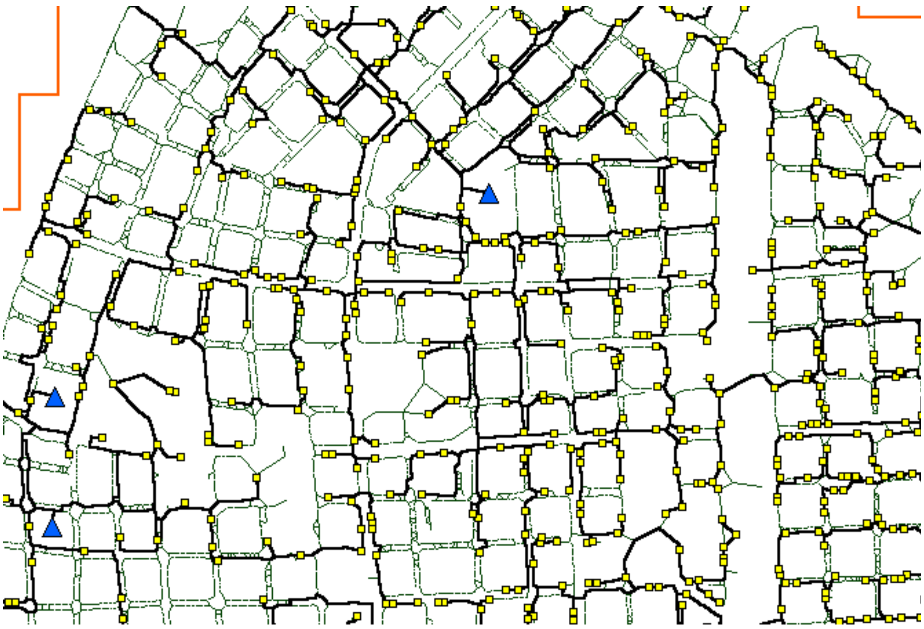

Figure 3: Distribution network design following street maps

Reference [4] presents an assessment of the impact of street maps on the length of the distribution networks. In order to perform this analysis, a urban area serving above one million consumers was planned by the greenfield RNM. Results showed that for the same distribution area, the LV grid calculated by the RNMs was 16.8% longer when street maps were considered. On the other hand, the length of the MV network obtained increased by 37.5% as compared to the situation where street maps are not considered. Naturally, this will have a significant impact on the distribution network costs.

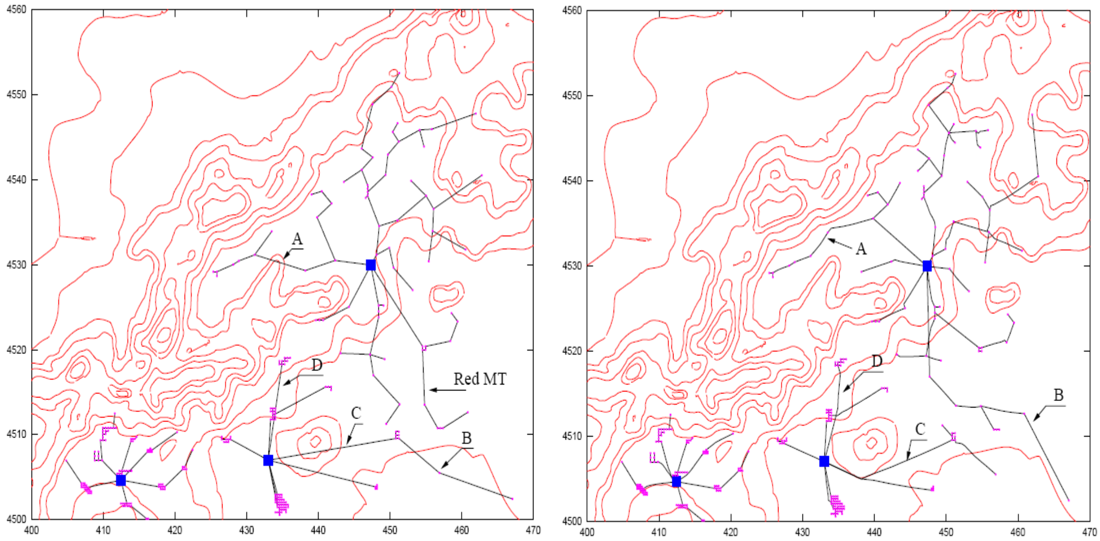

Figure 4: Distribution network design considering orography

Outside urban areas, distribution networks must observe some geographical constraints as well. For example, electrical lines cannot cross certain regions such as protected natural areas, rivers or seas. These regions are considered by the RNM by introducing the geographical coordinates of the vertexes of a polygonal outlines containing the forbidden regions. Furthermore, orography may also influence the design of distribution networks. Therefore, RNMs can interpret raster maps so as to avoid and skirt mountains or steep regions. Figure 4 displays two reference networks obtained for the same distribution area with and without considering geographical constraints. It can be seen that some lines have been modified and consumers transferred to a different feeder so as to avoid mountains (line C) or steep areas (lines A and B). Contrary to street maps, both forbidden regions and raster maps must be introduced as an exogenous input to the models.

Inputs

Given its complexity, the RNMs require extensive input data. The quality of these inputs greatly determines the quality of the final results. Thus, it is of utmost importance to correctly fine-tune this information so as to attain the desired results. The following information constitutes the most relevant inputs that must be provided to the RNMs:

i) Network users: loads, DG, EVs and storage

It is required to specify the exact location of every single user through its X, Y and Z coordinates, voltage level at the point of connection, contracted power or installed capacity and power factor. For large distribution areas, the number of consumers, particularly small LV consumers, can be very large. The networks studied can range from several thousand users up to a few million connections. Gathering all this information is one of the main difficulties of using the RNMs.

For those network users that can behave either as generators or as loads depending on their operation mode, i.e. EVs and/or storage, it must be specified in the input files whether the capacity assigned to them is being consumed or injected into the grid.

ii) Transmission substations

The RNMs do not optimise the location of transmission substations as this is generally out of the control of DSOs. Therefore, the location and capacity of these substations must be provided as an input to the models in any case. Notwithstanding, the expansion-planning model can decide to reinforce a transmission substation in order to avoid an unfeasible solution.

iii) Library of standardised network components

The RNM take into account the lumpiness of network investments as their decisions are made on the basis of a library of standard components. The library must comprise: HV power lines, and MV and LV feeders, HV/MV substations, MV/LV transformers, protection equipment (breakers, fault detectors and switches), maintenance crews, capacitor banks and voltage regulators. Whenever necessary, these elements must be differentiated per voltage level, type of area and whether they are built overhead or underground.

Several data ought to be provided for each one of the possible network components. These comprise basically the following: investment and maintenance costs, rated capacity, failure rate, electrical properties such as impedances and useful life. Moreover, in order to compute the expected indices of continuity of supply it is necessary to provide the models with a standard annual duration of preventive maintenance actions that are carried out on each type of component (HV line, MV/LV transformer, etc.), for overhead and underground elements and in each kind of area (urban or non-urban). Finally, fuzzy repair times in case of a contingency are assumed. Thus, the minimum, maximum and mean repair times must be provided with the same structure to that of preventive maintenance times.

The library of standardised elements determines to a great extent the quality of the results. A library which does not sufficiently reflect the real options that DSOs have when designing their networks will yield rather insignificant results. Hence, a lot of effort should be placed in the development of the library.

iv) Other modelling parameters:

In addition to the previous information, RNMs need various parameters in order to make all the computations involved. The most relevant ones are included in the following list:

- Simultaneity factors. As explained above, the RNMs require simultaneity factors to adequately design distribution networks.
- Economic parameters needed to calculate the present value of network costs and evaluate investment options. These comprise the cost of energy losses, the weighted average cost of capital (WACC) assumed and costs of ditches and posts to install conductors in different types of areas.
- Load modelling and GIS related parameters: density and minimum number of consumers to classify them into different areas and identify settlements, degree of undergrounding required within settlements per voltage level, impact of ground slope and height on costs and street maps parameters.
- Technical and quality constraints. In addition to the capacity constraints, the RNMs must observe the maximum and minimum bus voltages and the limits imposed on continuity of supply indices. The RNMs described in this report use the ASIDI and ASIFI indices as defined in [5]. Bus voltage limits are set per voltage level. MV network must comply with zonal and individual continuity indices, which are separately fixed for urban, semi-urban, concentrated rural, scattered rural and industrial areas.

Moreover, all the data corresponding to the initial network ought to be provided in the case of an expansion-planning RNM. This must include the topological as well as the electrical data for the existing network. Furthermore, the initial network users and the “new” incremental ones, either horizontal or vertical growths, must be differentiated.

Outputs

The results obtained by the RNMs are twofold. On the one hand, an html file summarises the most relevant information of the network designed and the corresponding costs adequately broken down per type of network component. Furthermore, the continuity of supply indices attained with the given grid are provided. An example of one of these html files can be found in Appendix 1.

On the other hand, detailed graphical output files are created by the RNMs. Each one of these files corresponds to a layer of a GIS which includes not only the geographical information for the elements included in that layer, but also the electrical information such as impedances, thermal capacity or peak power flow. The expansion-planning RNM provides all the former information differentiating between the initial network and the increments needed to accommodate the horizontal and vertical increases in network users.

Figure 5 shows two examples of reference networks, particularly HV and MV levels, obtained with the greenfield RNM from scratch. More information concerning these distribution areas can be found in [6]. Additionally, it can be seen in the image on the right in Figure 5 the population settlements that were identified by the model. Within these settlements, street maps were built in order to force the distribution network to follow it as explained above.

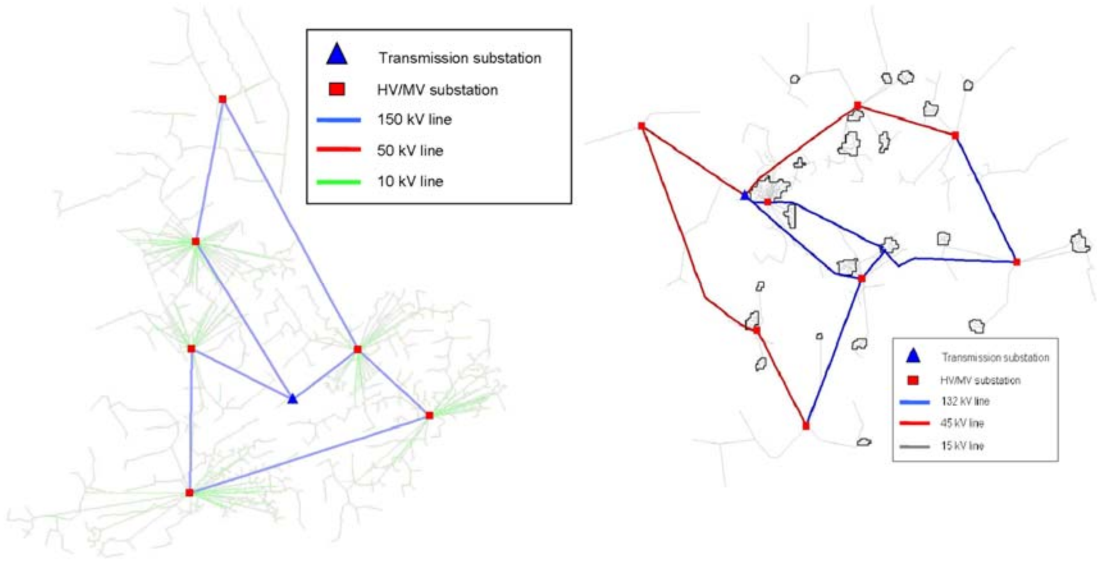

Figure 5: Examples of geographical representation of the outputs of RNMs

Architecture and algorithms

The functional architecture of the RNMs that will be used within the MERGE project is displayed in Figure 6. Furthermore, the main inputs needed for each one of the stages are shown in the figure. In the end, the objective function minimizes the one-off investment costs plus the present value of energy losses and maintenance costs for a specified number of years. The present value of annual costs is computed through a given WACC, considered the same for all costs. Given that heuristic planning algorithms are sequentially used, the results will provide a quasi-optimal reference network.

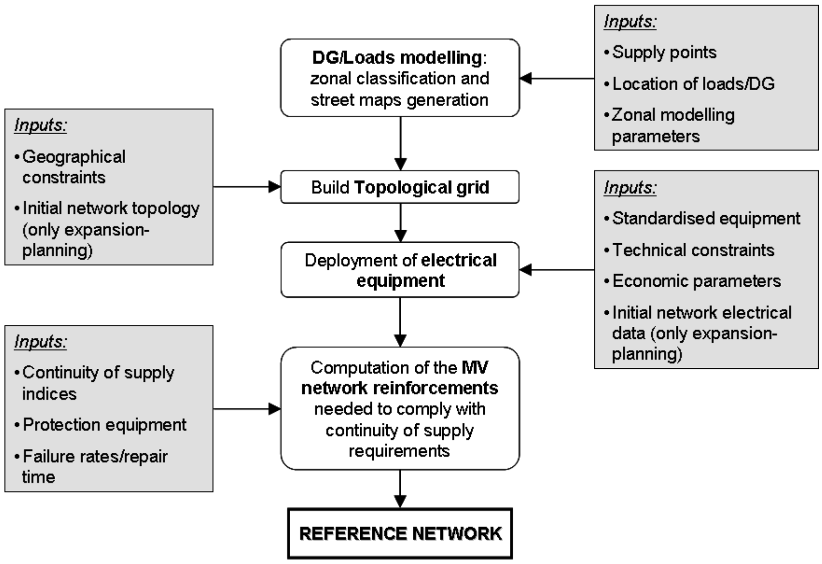

Figure 6: Logical architecture of RNMs: steps involved and relevant input data

Firstly, a DG/Loads modelling stage is performed in order to identify cities/towns and classify consumers into five categories: urban, sub-urban, concentrated rural, scattered rural and industrial areas. This classification is carried out according to the load density and number of customers of each kind and affects different aspects such as continuity of supply requirements for the consumers located in each type of area or whether overhead or underground lines are built. Additionally, the street maps within densely populated areas are automatically generated.

Secondly, an optimal network layout is computed. This topological network takes into account geographical constraints such as forbidden ways through, orography, street maps and, in the case of the expansion-planning RNM, the topology of the initial network. All geographical constraints but street maps are external inputs to the models. Note that the network resulting from this stage possesses electrical characteristics, albeit these are not still optimised.

At this stage, possible infeasibilities in future steps are avoided by means of a simplified preliminary electrical test. This is done by assigning to each branch and node of the topological network the network element with the largest capacity that can be found in the library of network elements, taking into account the type of area where each element of the grid is located, its voltage level and whether overhead and/or underground elements are possible. For instance, a long branch of the topological network may be removed if the voltage drop would surpass the maximum allowable value provided that that branch was built with the largest possible conductor found in the library loaded at its thermal rating.

The topological network is built through a bottom up approach. Initially, an estimate of the number of MV/LV transformers is obtained depending on the load density of different areas and the capacity of the MV/LV transformers included in the library of standard elements. These elements will be located at the centre of mass of the loads. Then, the LV topological grid is obtained through algorithms such as the Delaunay triangulation and the minimum expansion tree to connect the MV/LV transformers with LV network users. Similarly, the necessary HV/MV substations are estimated and the MV grid is designed to link HV/MV substations with MV network users and MV/LV transformers. The topology of initial MV and LV grids is radial. Finally, the HV grid is built connecting transmission substations with HV/MV substations and HV network users. The initial HV network is designed according to an N-1 reliability criterion, i.e. every load and substations must be supplied through at least two paths.

The expansion-planning RNM applies an additional algorithm to decide whether new network users are connected downstream of existing transformation capacity or alternatively new substation or transformers are required. Thus, new network users are classified into so-called feasible and unfeasible. Unfeasible network users are those that cannot be supplied by the initial network even when connected directly to a nearby substation because of capacity or voltage constraints. Furthermore, there are some users which could be supplied trough nearby transformation capacity without violating technical constraints, but are considered unfeasible since it would be less costly to supply them from higher voltage levels. In order to determine this, the cost of connecting these users to their voltage level in the initial network is compared to an estimation of the cost of building new transformation capacity and the necessary lines to connect these users to a higher voltage level. Once new network users have been classified into these two categories:

i) Feasible consumers are initially connected directly to the nearest substation or transformer and a heuristic branch-exchange algorithm is applied to optimise their connection to the initial grid. This algorithm seeks to minimise the present value of investment and maintenance costs as well as the cost of losses associated with the new connections.

ii) Unfeasible consumers are connected following the previously described methodology, taking into account the voltage level corresponding to the different network users.

Then, each segment or node of the topological network is assigned an optimally sized network element (line, transformer, etc.) by running a power flow for the network users given as input. At this step, technical constraints such as voltage and capacity limits are considered. Different power flow algorithms are used for HV meshed networks and MV/LV radial networks. More precisely, Gauss Seidel, Newton Raphson and radial power flow algorithms have been implemented. In any case, a 3-phase balanced system is assumed. The use of simultaneity factors at both ends of HV/MV substations and MV/LV transformers involves that the power entering one voltage level is not equal to the power supplied by the remaining voltage level. This requires modifying the modelling of these elements for power flow calculations as shown in Figure 7 and equation (1) [4].

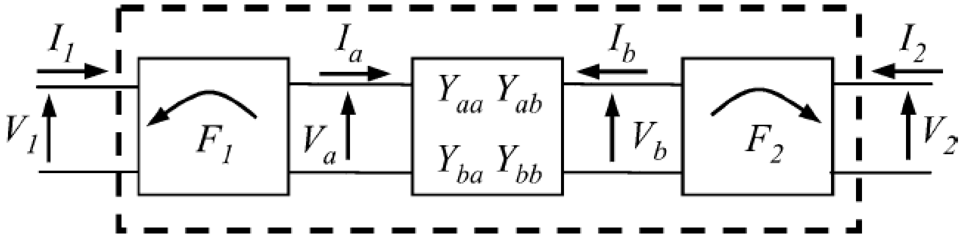

Figure 7: Two-port power flow model including simultaneity factors F1 and F2

$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} Y_{aa} \times F_1 & Y_{ab} \times F_1 \\ Y_{ba} \times F_2 & Y_{bb} \times F_2 \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix} \qquad (1)$$

The deployment of network components is done minimizing distribution network costs, including an estimate of energy losses computed as the product of power losses at peak demand times a representative loss factor. It is important to remark that despite the fact that energy losses can only be roughly estimated, they must be taken into account in order to adequately dimension grid components. For example, a specific conductor may suffice to support a certain power flow given its thermal capacity; however, the cost of losses may be such that thicker conductor can be more economic over the lifetime of the asset [7].

The computation of the energy losses must take into account the use of simultaneity factors. Otherwise, the difference between the power entering and exiting the substation due to simultaneity factors may be wrongly attributed to internal energy losses.

Real networks are not dimensioned merely according to current demand, but considering a future expected load growth. Hence, the RNMs assume a certain annual load growth for a number of years. Network components are thus sized in such a way that they may cope with the demand at the end of the growth period. After this growth period it is assumed that new network installations will be built and average flows will decrease. This effect is taken into account for the computation of energy losses along the expected life of the installations. This is shown in Figure 8. The demand of each network user or the generation capacity as well as the future load growth are considered deterministic.

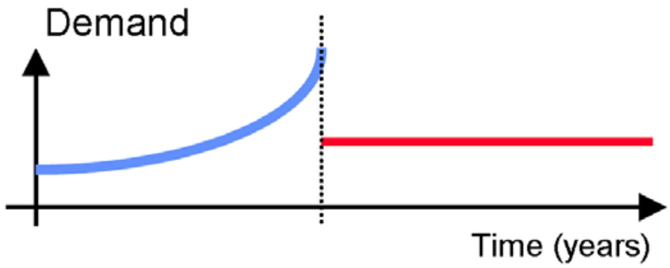

Figure 8: Vegetative load growth

Finally, continuity of supply constraints are incorporated to the initially radial MV grid. The final MV network must comply with the minimum continuity of supply indices set. These RNMs use ASIDI and ASIFI indices as defined in [5]. Both zonal and individual indices are taken into account. The failure rates of network elements are aggregated to compute the frequency of interruption of every load. Fault location and repair times are simulated taking into account the location (urban or rural) and type of network (overhead or underground). Additional equipment such as normally open meshing feeders, circuit breakers, maintenance crews or fault detectors might be placed if needed to comply with the continuity of supply requirements.

3 MODIFICATIONS PERFORMED ON THE REFERENCE NETWORK MODELS TO ACCOUNT FOR ELECTRIC VEHICLES

According to the description of work for Subtask 2.6 of the MERGE project, the RNMs must be able to evaluate the need for grid reinforcements due to the introduction of electric vehicles as well as to measure the impact of EV on short term operational issues such as energy losses and quality of service. In order to achieve this, the RNMs required some adaptations. These will be detailed below.

The RNMs were used in the IMPROGRES project supported by the EC to assess the impact of DG on distribution network costs. One of the major barriers pointed out in the IMPROGRES project was the fact that RNMs could only consider one scenario. This was due to the fact that distribution networks have been traditionally designed according to peak demand. Nevertheless, it was shown that large penetration levels of DG required analysing a wider range of possible scenarios. This required to combine the results of a greenfield RNM with an expansion-planning RNM [6]. In spite of this, the estimation of energy losses was not deemed too accurate.

From the perspective of the distribution network, EVs are extra loads that must be supplied through the grid. Additionally, under a V2G concept, EVs could behave as storage systems which will be consuming power during some periods and which may inject power back to the grid in others. Following this idea, the authors of [8] performed a preliminary assessment of the impact of EVs on distribution networks considering several charging modes and even the implementation of V2G. The methodology followed is similar to that of the IMPROGRES project. Nevertheless, the results obtained were limited by the fact that only two scenarios could be considered. The interaction of conventional electricity consumption and the charging of EVs throughout the day is a key issue with regard to the integration of EVs. However, this effect could not be adequately studied given the limited capabilities of the RNMs. This limitation is particularly relevant to analyse operational issues such as energy losses.

The MERGE project considers both purely electric battery vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). BEVs will have a higher storage capacity, thus requiring greater power consumption from the grid. Nevertheless, this does not imply a major difference with regard to the analyses performed with the RNMs as long as the differences in electricity consumption are appropriately included into the load profiles provided to the models as input.

In order to overcome the previous limitations, the expansion-planning RNM has been improved in order to overcome the barriers identified in previous studies. Thus, it is now possible to assign a specific consumption or production profile to each network user instead of a single value. RNMs work with a discrete number of scenarios, thus these profiles must be built through several load blocks. Depending on the requirements of the analyses, each one of these blocks can, for example, correspond to an hour of the day (24 blocks), morning-evening-night hours (3 blocks) or peak-valley situation (2 blocks). Power flows must be run for the whole distribution area analysed for each one of the scenarios provided. Hence, the higher the number of blocks, the more computational resources are needed.

As a result, a base network can be obtained with the greenfield model or alternatively take an existing network as a base case. Subsequently, the expansion-planning RNM can compute the reinforcements needed to cope with the integration of EVs and calculate the associated energy losses considering several scenarios simultaneously. These scenarios can reflect different patterns of battery charging such as the ones shown in Figure 9, Figure 10 and Figure 11 [9].

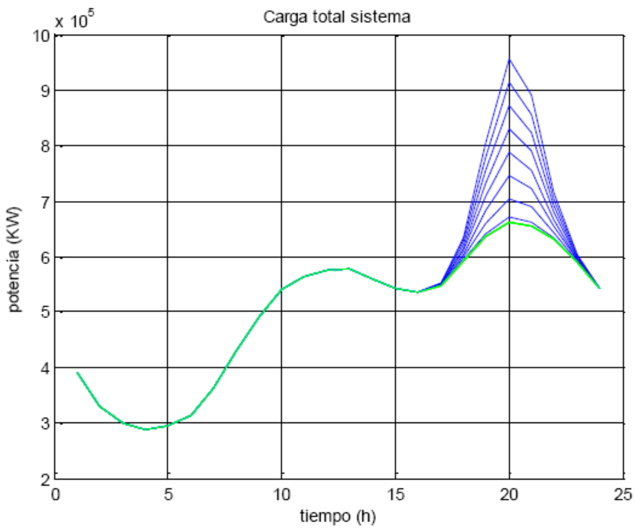

Figure 9: Load profile (kW vs hour of the day): battery charging at home during evening hours

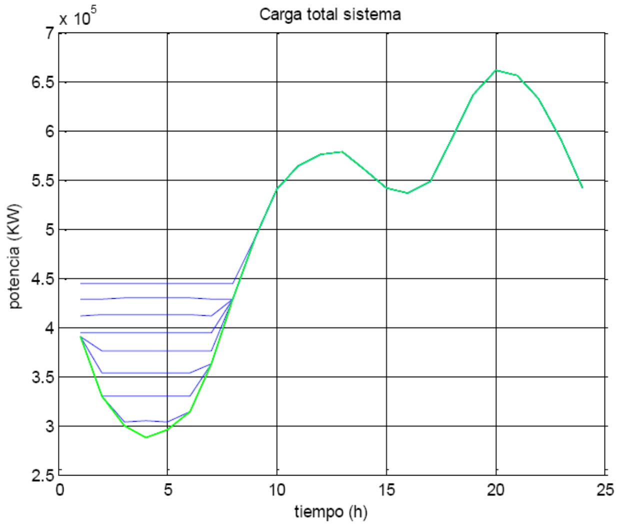

Figure 10: Load profile (kW vs hour of the day): battery charging at home during night hours

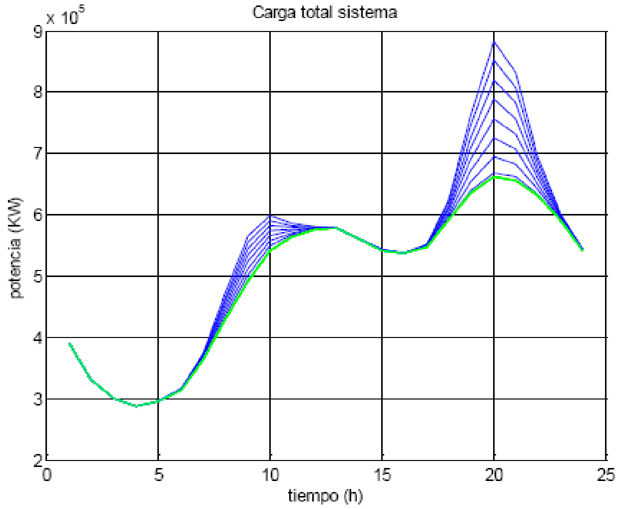

Figure 11: Load profile (kW vs hour of the day): battery charging at home during evening hours and at work in the morning

With regard to programming effort, this modification required to:

- Part of the inputs can be now a vector of values, instead of a single value. Therefore, some input functions and files had to be modified to allow the RNMs to function properly.
- Several variables such as power flows, energy losses, etc. become vectors. These vectors would have a component per each one of the scenarios studied.
- Each network element is dimensioned according to its most demanding situation, which does not necessarily coincide with that of other elements. For example, if EVs charge mostly during the night and are concentrated in a specific region, that area may have to be reinforced mostly due to the battery charging at night whereas the network elements in other regions may be dimensioned according to

peak demand in the evening hours. Consequently, the planning algorithms belonging to the third stage shown in Figure 6 now have to make their decisions based on the results obtained from several power flows.

– Output files required some adaptations so as to adequately provide the results for all the scenarios analysed, particularly concerning energy losses.

Furthermore, from a practical point of view, the following implications have to be taken into account when using the RNMs with several scenarios and EVs:

– The use of several scenarios requires more extensive input data which have to be obtained exogenously to the model.

– Since power flows are calculated for every scenario studied and planning decisions take into account all these results, computational efforts increase with the number of scenarios. This can be particularly relevant for very large distribution areas.

– Simultaneity factors have to be adapted to the mix of scenarios considered. On the one hand, the simultaneity factors traditionally used are representative for peak hours. However, if several scenarios are analysed, it may be needed to define different simultaneity factors for each period. On the other hand, the use of simultaneity factors can loose relevance if their effect is internalised in the load profiles assigned to network users.

– Loss factors represent the ratio of average losses over peak losses, typically on an annual basis. However, if a wider range of scenarios are considered, the use of approximate loss factors can be substituted with more accurate estimations of energy losses. Nevertheless, the RNMs will provide a limited number of power losses in any case. In order to translate the power losses into energy losses, it is required to assign some kind of loss factor to each one of the scenarios. This can be done by considering that each scenario analysed is representative of a certain number of hours per year.

4 REFERENCES

[1] Ministry of Industry, Tourism and Trade, "Royal Decree 222/2008, of February 15th, that establishes the remuneration regime for the electricity distribution activity (In Spanish)" February 15th, 2008.

[2] Cossent, R, Olmos, L, Gómez, T, Mateo, C, Frias, P. "Distribution network costs under different penetration levels of distributed generation". European Transactions on Electrical Power, *Accepted for publication.* DOI: 10.1002/etep.503

[3] Cossent, R, Olmos, L, Gómez, T, Mateo, C, Frias, P. "Mitigating the impact of distributed generation on distribution network costs through the implementation of advanced response options". Presented at the 7th International Conference on the European Energy Market, 23-25 May, 2010. Madrid, Spain.

[4] Mateo, C, Gómez, T, Sánchez-Miralles, A, Peco, J, Candela, A. "A reference network model for large-scale distribution planning with automatic street map generation". IEEE Transactions on Power Systems, *Accepted for publication. http://dx.doi.org/10.1109/TPWRS.2010.2052077*

[5] "IEEE guide for electric power distribution reliability indices," IEEE. Std 1366, 2001 Edition, 2001.

[6] Cossent, R, Olmos, L, Gómez, T, Mateo, C, Jeroen de Joode, Scheepers, M, Nieuwenhout, F, Poot, J, Bongaerts, M, Trebolle, D, Doersam, B, Bofinger, S, Cali, U, Gerhardt, N. "Case studies of system costs of distribution areas. D5 IMPROGRES Project". Available on-line at www.improgres.org

[7] Peco, J. "Model for designing electrical distribution grids with geographical constraints" (In Spanish). PhD dissertation. Universidad Pontificia Comillas. Madrid, 2001.

[8] Pieltain, L, Gómez, T, Cossent, R, Mateo, C, Frías, P. "Assessment of the impact of plug-in electric vehicles on distribution networks". IEEE Transactions on Power Systems, *Accepted for publication.*
http://dx.doi.org/10.1109/TPWRS.2010.2049133

[9] Rosso, A. "Evaluation of the impact of electric vehicles on distribution grids" (In Spanish). MSc thesis, Universidad Pontificia Comillas. Madrid, 2010.

APPENDIX 1 – EXAMPLE OF HTML OUTPUT FILE

Summary of network users:

– Loads per voltage level

	Individual consumers	Number of supply points	Contracted power (MW)	Peak demand (MW)	Energy consumption (year 0) (MWh)	Average power factor
LV	61304	27577	291.11	163.02	485541.91	0.96
MV	268	354	103.86	62.31	163759.08	0.96
HV	5	5	13.00	13.00	34164.00	0.96
TOTAL	61577	27936	407.96	238.33	683464.99	0.96

– DG per voltage level

	Number	Installed capacity (MVA)
DG_LV	0	0.00
DG_MV	0	0.00
DG_HV	0	0.00
TOTAL	0	0.00

Summary of network components:

– Conductors

	Length (km)		Investment cost	Preventive maintenance (annual)	Corrective maintenance (annual)
	Overhead	Underground			
LV grid	538.33	144.64	6610219.63	4104.65	83976.48
MV grid	569.02	108.72	17211647.02	395635.42	521060.00
HV grid	205.31	1.12	11100341.25	254339.14	86471.29
TOTAL	1312.66	254.48	34922207.91	654079.21	691507.77

– Distribution substations and MV/LV transformers:

	Number	Iron losses (MW)	Copper losses (MW)	Demand (MVA)	Capacity (MVA)	Investment cost	Preventive maintenance (annual)	Corrective maintenance (annual)
MV/LV transformers	389	0.33	0.90	153.18	209.10	8221764.74	475521.09	19971.63
HV/MV substations	8	0.32	1.21	126.23	240.00	11357965.21	384647.76	192.32

Break-down of distribution network costs:

	Investment cost		Preventive maintenance (annual)			Corrective maintenance (annual)		Losses year 0		TOTAL (NPV)	
	euro	%	euro	%	hours/year	euro	%	euro	%	euro	%
LV grid	12999365.02	19.22	4104.65	0.25	683	83976.48	11.80	283924.45	30.33	18161565.76	15.05
MV/LV transf.	8221764.74	15.09	475521.09	31.40	9824	19971.63	2.81	193635.37	20.68	19398312.39	16.07
MV grid	23836304.08	35.25	511066.65	31.36	3389	521143.82	73.22	220482.67	23.55	44791552.90	37.11
HV/MV subst.	11357965.21	16.79	384647.76	23.60	2600	192.32	0.03	205944.01	22.00	20745577.35	17.19
HV grid	11212567.22	16.58	254339.14	15.61	126	86471.29	12.15	32236.62	3.44	17615252.66	14.59
TOTAL	67627966.28	100.00	1629679.29	100.00	16622	711755.55	100.00	936223.13	100.00	120712261.06	100.00

Break-down of energy losses:

	Losses year 0				Losses year N			
	Energy (MWh)	%	Power (MW)	%	Energy (MWh)	%	Power (MW)	%
LV grid	7706.96	30.33	2.93	33.68	10932.47	32.49	4.16	34.44
MV/LV transf.	5256.12	20.68	1.23	14.14	6247.78	18.57	1.61	13.32
MV grid	5984.87	23.55	2.63	30.18	8489.65	25.23	3.73	30.86
HV/MV subst.	5590.23	22.00	1.53	17.60	6741.99	20.03	2.04	16.87
HV grid	875.04	3.44	0.38	4.41	1241.27	3.69	0.54	4.51
TOTAL	25413.22	100.00	8.71	100.00	33653.16	100.00	12.08	100.00
Losses in % wrt demand	3.72%		3.65%		4.92%		5.07%	

Break-down of the cost of posts and ditches:

	Length (km)				Cost			
	Facade	Post	Ditch	Total	Facade	Post	Ditch	Total
BT	244.75	48.78	89.64	383.17	1154957.69	48814.42	5185373.28	6389145.38
MT	0.00	70.98	46.88	117.86	0.00	334933.44	4573220.85	4908154.29
AT	0.00	0.00	1.12	1.12	0.00	0.00	112225.97	112225.97
TOTAL	244.75	119.76	137.65	502.15	1154957.69	383747.86	9870820.09	11409525.64

Protection and other equipment to improve quality of supply:

		Number	Investment cost	Preventive maintenance (annual)	Corrective maintenance (annual)
Reclosers		47	742101.80	74166.00	4.70
Fault detectors		69	29049.00	2898.00	6.90
Switches		717	377357.10	37284.00	71.70
Total Protections		833	1148507.90	114348.00	83.30
Capacitors		0	0.00	0.00	0.00
Voltage regulators		0	0.00	0.00	0.00
Total voltage control		0	0.00	0.00	0.00
Maint. crews (corr)		7	567994.87	1083.23	0.52
Maint. crews (prev)		1.88	--	--	--
Normally open feeders	Km overhead	133.43	3068538.04	78569.25	66585.58
	Km underground	10.99			

Continuity of supply indices per type of area:

Zone	Number MV/LV transf.+MV consumers	Installed capacity (MVA)	ASIDI	ASIFI
Urban	620	503.211	2.08	1.00
Semi-Urban	0	0.000	0.00	0.00
Concentrated rural	0	0.000	0.00	0.00
Scattered Rural	0	0.000	0.00	0.00
Industrial	118	131.449	0.74	0.34

Detailed list of network components:

– MV/LV transformers:

Type of element	Code	Sn(kVA)	Reliability zone	Number	Average ratio Load/Capacity (pu)	Capacity (MVA)	Investment (euros)
CCTT	CT3_S	400	P	3	0.722	1.200	71382.21
CCTT	CT4_S	630	P	25	0.754	15.750	627005.88
CCTT	CT5_S	800	P	18	0.778	14.400	464245.93
CCTT	CT6_S	1000	P	13	0.761	13.000	343759.77
CCTT	CT1_A	15	U	23	0.404	0.345	170983.85
CCTT	CT2_A	25	U	7	0.611	0.175	52578.04
CCTT	CT3_A	50	U	16	0.577	0.800	123183.44
CCTT	CT1_S	100	U	8	0.670	0.800	157752.82
CCTT	CT4_A	100	U	22	0.600	2.200	178103.93
CCTT	CT2_S	250	U	20	0.688	5.000	447633.82
CCTT	CT5_A	250	U	16	0.504	4.000	147897.06
CCTT	CT3_S	400	U	41	0.725	16.400	975556.84
CCTT	CT6_A	400	U	4	0.701	1.600	41604.83
CCTT	CT4_S	630	U	80	0.703	50.400	2006418.81
CCTT	CT7_A	630	U	1	0.740	0.630	12173.78
CCTT	CT5_S	800	U	48	0.760	38.400	1237989.14
CCTT	CT6_S	1000	U	44	0.755	44.000	1163494.61

– LV lines:

Type of element	Code	Sn(kVA)	Reliability zone	Number	RAverage ratio Load/Capacity (pu)	Length (km)	Investment (euros)
LINEA_BT	3X50	107	P	577	0.08	8.51	55336.58
LINEA_BT	3X95	173	P	326	0.18	5.29	43732.86
LINEA_BT	3X150	218	P	287	0.25	5.05	52737.40
LINEA_BT	3X240	288	P	666	0.44	15.99	223503.81
LINEA_BT	3X25	62	U	8601	0.10	131.80	727935.02
LINEA_BT	3X25	69	U	410	0.12	64.66	731393.81
LINEA_BT	3X50	92	U	3982	0.23	70.90	489455.07
LINEA_BT	3X50	107	U	2918	0.08	39.21	254865.79
LINEA_BT	3X50	114	U	171	0.24	27.52	389012.11
LINEA_BT	3X95	143	U	6484	0.39	227.28	2133668.11
LINEA_BT	3X95	159	U	78	0.34	10.91	209811.82
LINEA_BT	3X95	173	U	945	0.18	14.34	118615.66
LINEA_BT	3X150	211	U	32	0.49	5.26	133899.31
LINEA_BT	3X150	218	U	746	0.25	13.98	145884.64
LINEA_BT	3X240	288	U	1354	0.39	42.26	590467.64

– MV lines:

Type of element	Code	Sn(kVA)	Reliability zone	Number	Average ratio Load/Capacity (pu)	Length (km)	Investment (euros)
LINEA_MT_R	3X50	4027	P	55	0.11	5.29	148033.23
LINEA_MT_R	3X95	6495	P	19	0.24	2.13	63832.24
LINEA_MT_R	3X150	8184	P	8	0.30	0.96	31029.18
LINEA_MT_R	LA145	9717	P	1	0.60	2.16	85400.04
LINEA_MT_R	3X240	10782	P	15	0.37	1.84	66767.93
LINEA_MT_R	LA240	13510	P	5	0.79	6.04	341077.04
LINEA_MT_R	3X400	14030	P	15	0.58	1.35	58641.59
LINEA_MT_R	LA30	3455	U	307	0.09	408.84	7698076.50
LINEA_MT_R	3X50	4027	U	177	0.12	53.40	1493229.35
LINEA_MT_R	LA56	5196	U	34	0.37	60.21	1430578.50
LINEA_MT_R	3X95	6495	U	34	0.24	9.71	290752.30
LINEA_MT_R	LA80	6573	U	13	0.50	31.53	852139.09
LINEA_MT_R	3X150	8184	U	21	0.32	7.00	226799.48
LINEA_MT_R	LA145	9717	U	10	0.53	14.54	573972.54
LINEA_MT_R	3X240	10782	U	14	0.39	3.42	124477.18
LINEA_MT_R	LA240	13510	U	3	0.78	3.26	183883.70
LINEA_MT_R	3X400	14030	U	7	0.49	4.02	174448.63

– HV lines:

Type of element	Code	Sn(MVA)	Reliability zone	Number	Average ratio Load/Capacity (pu)	Length (km)	Investment (euros)
LINEA_RAT	Hawk45	47	X	6	0.38	77.35	2939374.65
LINEA_RAT	Hawk132	139	X	10	0.40	124.70	7663538.92
LINEA_RAT	Condor132	190	X	1	0.68	3.25	269449.49
LINEA_RAT	Condor132S	190	X	1	0.27	1.12	227978.19

– HV/MV substations:

Type of element	Code	Sn(MVA)	Reliability zone	Number	Average ratio Load/Capacity (pu)	Capacity (MVA)	Investment (euros)
SSEE	S_A_0	20	U	4	0.350	80.000	2400000.00
SSEE	S_A_3	20	U	2	0.161	40.000	3446443.81
SSEE	S_A_5	40	U	1	0.698	40.000	2179991.11
SSEE	S_A_7	80	U	1	0.798	80.000	3331530.30