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OPTIBAT Study

"Optimal location of electrical energy storage systems based on batteries"

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1 Introduction

In recent years, there has been a strong increase in electricity generation based on the use of renewable resources, such as wind generation and solar photovoltaics. Both technologies have and will have an increasingly relevant weight within the generation mix. However, both wind generation and solar photovoltaics are not dispatchable and therefore can cause a series of problems such as overvoltages, stability and security issues in the electricity network especially in the event of failures. In addition, this problem is exacerbated by the increase in distributed photovoltaic installations of residential or commercial nature, given the limited controllability and observability that system operators have over such facilities. Consequently, this situation requires greater flexibility of the system to guarantee stability and safety in the electricity network. Batteries can provide such flexibility by being able to provide services to the system to improve the integration of renewable energies such as load and demand management, frequency and voltage control, outage management, etc. Moreover, the progressive decline in cost that is taking place in storage technologies, especially lithium-ion technology, raises its potential use in electricity networks.

At present, power systems use energy storage mainly based on hydroelectric pumping stations. Owing to the high capacity of these power plants, they are usually connected to the transmission network. In the case of storage with batteries, unlike what happens with pumped storage, its location in the electric network does not necessarily have to be the transmission network. Due to the modularity they can be designed with, there can be storage solutions based on batteries connected to the transmission networks, to the distribution networks or directly at the customers' facilities.

Electrical storage based on batteries can provide a variety of services to the electrical system because it can operate in all four quadrants (active and reactive power control) and modify the power that is delivered or consumed very quickly. These services include demand management, reduction of peak demand, management of overloads, absorption of power variations from renewable resources (wind variations or passage of clouds), frequency and voltage control, etc. However, the storage capacity needed to provide the different services efficiently can be influenced by the location and size of batteries installed within the electrical system. Therefore, it is important to consider whether there is an optimal storage location where a greater benefit for the complete power system is achieved.

2 Objective of the study

The objective of this study is to analyze the most suitable location and distribution of storage systems based on batteries to improve continuity of supply (outage management). For this purpose, the impact of the introduction of batteries in the transmission network and the distribution network has been analyzed and quantified, in order to compare which of the two is optimal in relation to the reduction of energy not supplied. Additionally, the impact on other aspects such as the improvement of load profile, voltage levels and the reduction of losses has been evaluated. The study has considered the expected growth in demand from the electric vehicle and renewable generation, as well as a moderate penetration of photovoltaic self-consumption in order to assess the extent to which battery storage can facilitate the integration of these new demand and generation technologies into the electrical network.

The study compares the technical capability of two alternative solutions. In the first solution, batteries are installed in the transmission network in large-size units. In the second alternative batteries are installed in the Medium Voltage (MV)[1] distribution network in smaller-size units. To compare both cases, the two proposed solutions have the same economic budget, limited to a sufficiently significant value to produce a positive impact on the quality of supply of the case under study, but not too high to avoid saturating with storage all the nodes in the network.

The possible allocation of batteries in the Low Voltage (LV) distribution networks, in the customers' facilities or "behind the meter" (BTM) has not been considered in this study. Firstly, the costs of BTM batteries are higher. Effectively, according to a study by the MIT[2], for the same installed power the cost of batteries at LV is higher than at MV due to the lower unit-power of the batteries, which causes a rapid decrease in economies of scale. Moreover, the communications needed for the management of a fleet of batteries of thousands of units installed at LV would have greater cost and less reliability for its management than that of a few hundred units connected at MV, or a few units connected at High Voltage (HV). Likewise, it must be taken into account that in the case of BTM batteries, the availability of the energy stored in the batteries depends on the interests of the customer, so their availability would not be fully guaranteed in case of need by the network operators. Another drawback associated with the installation of batteries in low voltage is the obligation to disconnect such batteries in the event of an incident in the LV network they are installed in to avoid situations of risk, so they could not provide support to the network in those situations, although they could provide power to the customer's own installation. Finally, it must be taken into account that the impact on the quality of service provided to LV customers under faults at HV or MV is greater than under faults at LV, so moving the batteries from MV to LV would not substantially improve the quality of service.

Based on the results obtained for the two case studies, the conclusions of the study have been extracted regarding the optimal location of battery based electric storage systems, either in the transmission network or in the distribution network.

[1] HV Un ≥ 45 kV; MV 1 ≤ Un < 45 kV; LV < 1 kV

[2] Utility of the Future. An MIT Energy Initiative response to an industry in transition. Chapter 8, page 297. http://energy.mit.edu/wp-content/uploads/2016/12/Utility-of-the-Future-Full-Report.pdf

3 Grid storage

The main characteristic of electrical storage in relation to networks is its flexibility, understood as the capacity to provide multiple services [1] related to the balance of active and reactive power.

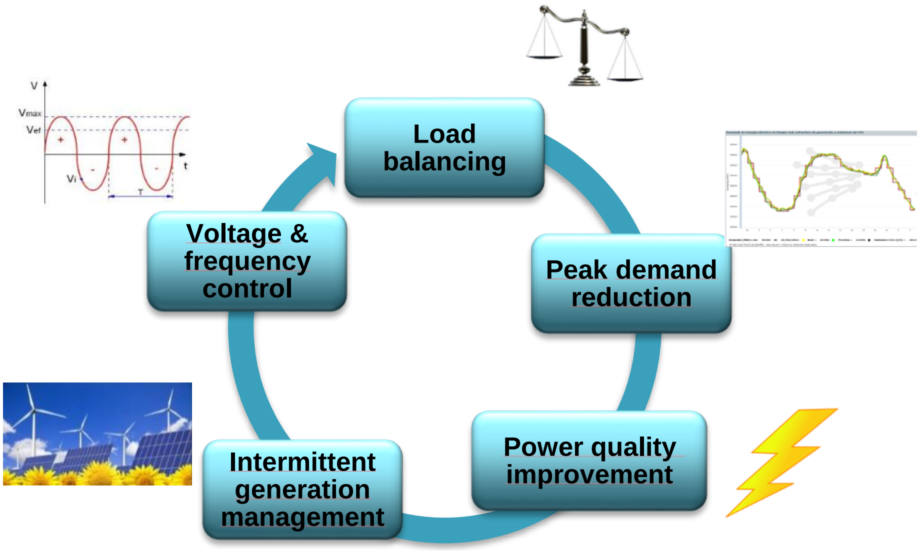


Figure 1. Flexibility services provided by storage

Thus, the following can be mentioned as main services:

1. Load balancing. Storage can help to reduce the fluctuations in demand of the network area in which it is located, between the peak hours and the valley hours, contributing to a better use of network elements. At the same time, it allows price arbitrage in those systems in which energy is negotiated on an hourly basis, shifting demand from the most expensive hours to the cheapest ones.
2. Peak demand reduction. The operation of storage as a generator in the hours of greatest consumption helps to reduce the peak demand in the network, releasing network capacity and reducing the power term of the bill to those consumers who shift part of their consumption to other hours of lower demand.
3. Quality of supply improvement. During a network fault leading to a blackout, storage can operate as a backup generator, supplying power to those end consumers who have it. Moreover, distributed storage in the network also contributes to improve the quality of supply for all consumers in the network. Effectively, under fault conditions storage helps to reduce the loss of demand by releasing part of the network and allowing a better use of it getting support from other adjacent healthy areas.
4. Intermittent generation management. Storage can contribute to reduce generation fluctuations associated with intermittent renewable sources, by opposing such variations exporting when there is a deficit or absorbing when there is excess of renewable generation. This service can be provided from the generation facility itself or distributed within the network.

5. Voltage and frequency control. Storage contributes to frequency control in all periods of operation of this service, with the only limitation of the available energy capacity. With regard to voltage control, when the storage facilities are based on batteries, it is possible to use the inverter's control capacity to provide reactive power, in addition to the management of active power.

The fact that electrical storage has the ability of offering multiple services, together with its modularity when it is based on electric batteries, makes the decision about its optimal location and sizing can be approached from different perspectives, fundamentally in relation to the type of service to be provided. According to [2], the existing literature on energy storage can be grouped into three categories: operation, size and location.

In relation to the operation of storage, the problem to solve is how to optimally dispatch storage facilities to provide one or several services together. Thus, in [3] the optimum dispatch of a battery is determined with a fifteen-minute resolution to minimize losses, the cost of supply, the installation cost and to manage the variability of photovoltaic generation in a medium voltage distribution feeder. In [4] a study is proposed for a medium size MV distribution network (869 nodes, 387 loads and 197 km of lines) that seeks to determine the location, size and optimal dispatch of batteries, with a resolution of half an hour, to minimize the peak demand of the network and manage the integration of photovoltaic generation. The study uses a model that defines the net benefit associated with the delay of investment in the network as a function of the growth rate of the peak demand, the investment savings in peak power, the energy arbitration (photovoltaic integration), the size and location of the battery. In [5] and [6] a similar study is proposed which seeks to determine the value of storage connected to the low voltage node of the MV/LV transformers to reduce the peak demand by means of a reference network model. The value of storage is determined as the difference between savings in network reinforcements and the cost of batteries. The study analyzes three large distribution networks (urban, semi-urban and rural) and determines that, by increasing the size of the battery, savings in network investments are reduced, being higher in the urban network. In [7], [8] and [9] the optimal dispatch of batteries is analyzed to minimize a multi-objective function that includes the cost of losses, the reduction of peak demand and voltage control. The characteristic of the three studies is that they apply to small distribution network models. Finally, in relation to studies that address the optimization of batteries operation, in [10] and [11] two papers jointly analyze the distribution and transmission networks of the islands of Hawaii and Maui, in the archipelago of Hawaii. In [10] an optimal dispatch that minimizes the variations of photovoltaic generation and the demand peak in the distribution network is presented, with the aim of unloading the transmission network. In [11], the location of batteries in the transmission network is analyzed to minimize generation losses and frequency deviations, and in the distribution network to reduce the peak demand and smooth demand variations. It should be noted that, although the same criterion is used to locate the batteries in nodes of the transmission and distribution networks, a comparison is not made between both locations, since the objective of the different dispatch is separate for each network.

Concerning the optimal size of storage, in [12] a cost-benefit analysis of multiple scenarios is proposed to determine the optimal sizing of a battery to improve voltage regulation, reduce the peak of photovoltaic generation, displace the peak demand and maximize the operating life of the battery in a medium voltage distribution network. The optimal size is determined in two stages. In the first one, the dispatch of the battery is obtained for a fixed power and a profile of photovoltaic generation and network demand. The dispatch seeks to maintain the voltage in the nodes within limits and minimize the number of operations of the voltage control devices. In the second stage, a cost-benefit analysis is carried out, so that different battery sizes and different penetration levels of photovoltaic generation can be compared. In [13] a study is presented to obtain the optimum sizing and the optimal location of batteries in low voltage distribution networks with high penetration of photovoltaic generation. The objective sought is to minimize the cost of production plus the cost of the batteries. The study compares between the centralized storage location in the secondary substation and the distributed location at the customers' end. It is concluded that the preferred location is the distributed one, because it results in a lower curtailment of photovoltaic generation. In [14] a similar problem is analyzed but the objective function seeks to minimize the cost of conventional generation. Finally, in [15] the optimum power of batteries and their location in a distribution network with wind and photovoltaic generation is determined. The optimization problem is posed to minimize the net present value of the network with the batteries. The study concludes that the minimum net present value is obtained for 2 batteries, increasing as the number of batteries installed increases.

Regarding the assessment of the optimal location of storage plants, [16] presents a methodology that seeks to determine the optimal location of distributed storage to minimize voltage deviations in all nodes of a distribution network with high penetration of photovoltaic generation, assuming that the total storage capacity to be installed is known. The study concludes that, with a fixed storage power, by increasing the number of possible nodes in which to install batteries, the control of the network voltage is improved. That is, storage is more effective the more distributed it is. Finally, in [17] the problem of deploying storage on a large scale in a transmission network with conventional generation and wind generation is studied. For a fixed amount of storage capacity, the optimal distribution of storage is determined in each node of the network along with its dispatch, taking into account the constraint in the network. The results show that an important part of storage is located in the nodes with greater demand, being the optimal location highly dependent on the structure of the network and quite robust in relation to the location of wind generation. Additionally, the location is quite independent of the storage size that is located in each node of the network.

The analysis shows it is possible to address the problem of sizing and location of batteries in transmission and distribution networks as an optimization problem under different criteria. These depend on the service or set of services that batteries will provide. Therefore, the solution is not unique and it is highly dependent on the case under study. In most cases, a multiple dispatch objective is sought to maximize the use of the batteries. It should also be noted that, in most studies, the problem is analyzed for a small study network and in none of them a comparison is made between the location of batteries in the transmission network and in the distribution network to provide the same service, or a set of similar services.

4 Methodology

The purpose of the study is to assess the effect of deploying batteries in the transmission and distribution networks to improve continuity of supply (outage management) and facilitate the integration of renewable generation and electric vehicles.

In relation to the quality of supply, the reduction of energy not supplied during loss of load events has been assessed both in the transmission and in the distribution networks.

Regarding the integration of renewable generation and electric vehicles, the study has analyzed the improvement in voltage levels, the reduction of losses and the load factor (peak demand compared to nominal demand) provided by the charging/discharging management of batteries.

An important aspect to consider is the performance of electrical storage with a growth of renewable generation, especially solar photovoltaic, together with the increase in demand and the penetration of electric vehicles. For this reason, the study has started from the current state of the transmission and distribution networks, from which a future study scenario has been built. The new scenario incorporates the expected demand growth in the medium term (year 2025) and a penetration of renewable generation (centralized and self-consumption) and of electric vehicle greater than the current one, with the aim of realizing the benefits of installing storage in the networks.

In the created scenario, the study of overvoltages/overloads has been carried out by means of a contingency analysis, both in the transmission and distribution networks, to determine the optimal locations for the installation of batteries (where the total energy not supplied is minimized). Next, the technical differences - usefulness of the batteries - between the two studied cases were analyzed. The aspects evaluated in each case include the energy not supplied in case of loss of load events, as the main objective, with electrical losses, nodal voltages and load levels in lines and transformers as secondary objectives.

Consequently, the methodology applied to carry out the study has been structured in the following stages, which are described with more detail in the following sections:

- Definition of the 2025 study scenario and contingency analysis in the transmission and the distribution networks
- Determination of location and optimal size of batteries to minimize the Energy Not Supplied (ENS) during loss of load events
- Simulation of the operation of charging/discharging the batteries that optimizes the operation of the electrical system
- Analysis of results and conclusions. Comparison transmission VS. distribution location

4.1 Network model

The study scenario for 2025 is obtained from the current situation of the network, incorporating in the network model the expected growth of electricity demand, as well as the renewable generation (centralized and self-consumption), the demand of electric vehicles and batteries storage. The following sections detail the considerations applied in this study for the modeling of these elements in the future study scenario.

4.1.1 Electrical demand

The construction of the future scenario requires an estimate of the electricity demand in that scenario. This estimate is obtained by applying a variation rate to the base case demand, calculated based on the number of years of the study horizon and the annual growth rate considered by the system operator in its transmission network development studies.

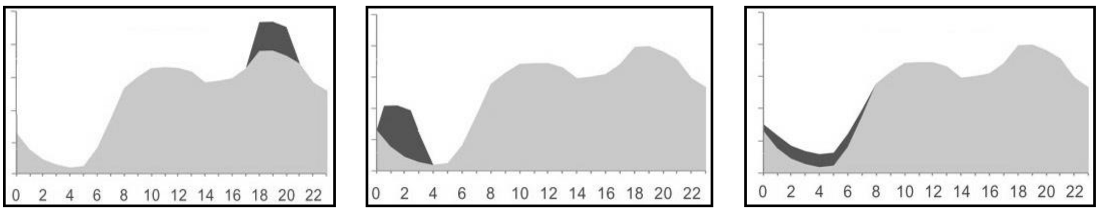
However, part of the demand will be associated with the increasing presence of the electric vehicle so, given the particular behavior of this type of consumption, it is also necessary to make an estimate of its associated demand to be able to assess a more realistic demand scenario in the near future.

4.1.2 Electric vehicles

Regarding the electric vehicle, a significant increase in the number of plug-in electric vehicles (EV) is expected in the coming years. These vehicles will be charged mostly through low voltage networks. The charge of a significant number of EVs can cause a series of problems in low voltage networks such as line and transformers congestion, voltage drops, increased losses, reduction in the operating life of secondary substations, etc.

There exist different alternatives to charge EVs

- Non-controlled charging, so that the charge of the EVs is done upon arrival at home after the last trip of the day, generally between 5 and 9 pm (Figure 2.a)
- Night charging through the implementation of night charge rates (Figure 2.b)
- Smart charging, consisting in distributing the demand of EVs in an optimal way to minimize the possible impacts on the electric networks (Figure 2.c). The smart charging of the EV can be unidirectional and bidirectional (V2G), that is, in addition to consuming energy from the network, the EV can also return power to the network at certain times, if necessary.



(a) (b) (c)

Figure 2. EV charging strategies and their impact on load profile (a) Non-controlled, (b) night charge and (c) smart charging

Given the uncertainties about the viability of the business model that exploits the bidirectional smart charging and the greater complexity involved in its modeling, the EV discharge has not been considered as an alternative to storage in the study. Effectively, due to the low penetration of EV most of their charging is done as non-controlled, that is, the user connects the EV to the network without any technical criteria. However, the offer of off-peak and lower off-peak rates will improve the integration of EVs and reduce the cost of charging. In this study, it is assumed that most users with EV will use this type of tariffs. Taking into account the hourly price of energy and the average duration of the daily journey, an estimate of the need to charge electric vehicles can be made. In this study, we have considered a distribution of the total hourly demand of the electric vehicle proportionally to the demand of each node of the network.

4.1.3 Centralized generation

The development of the future scenario also requires an estimate of generation available to supply existing demand. Regarding centralized generation, the existing plants are considered, as well as the new generation facilities that have connection authorization.

The centralized renewable generation facilities are modeled by their hourly generation, determined from the hourly solar radiation curve, in the case of photovoltaic installations, and the average wind generation curve, in the case of wind installations. The use of the mean hourly power for wind generation, although it is not realistic, does not affect the reliability of the model, since this generation is connected to the transmission network and its variability is compensated by other backup, thermal power plants and hydroelectric plants.

4.1.4 Self-consumption

In the coming years, a progressive increase in the number of self-consumption facilities is expected, specifically of photovoltaic self-consumption. For this reason, the future scenario must also consider the most probable evolution of this type of generation. Previous studies have indicated that residential photovoltaic generation systems will be concentrated mainly in rural areas due to the greater amount of roof available. Thus, this study considers a level of adoption of photovoltaic self-consumption of 20%.

The photovoltaic self-consumption installations are modeled in the future scenario by incorporating generators in the demand nodes, with the hourly generation determined from the hourly solar radiation curve. The nominal power of the self-consumption generators is calculated so that the annual energy generated is equal to 20% of the energy consumed by the customer. The methodology used to determine the installed power and the location of the self-consumption facilities in the distribution network is fully described in [18].

4.1.5 Electric batteries

Batteries are included in the network model as generators. A positive injection of power means that the battery is discharging, while a negative injection means that it is charging. In this study, it is considered that the main objective of the batteries is the improvement of the quality of supply by means of the reduction of the energy not supplied. So, the nominal power and the location of batteries in the two location cases considered (in the transmission network or in the distribution network) are determined as a result of a contingency analysis.

The hourly power consumed/generated by the batteries is obtained as a result of the charge/discharge of the batteries by solving an optimization problem that allows the assessment of the optimal dispatch of batteries in the network.

In the operation of the batteries, a minimum and maximum state of charge (SOC) and a maximum number of cycles per year are established, in order not to compromise the useful life of the battery. The minimum SOC is set at a value that does not compromise the functionality of the batteries to manage outages (main objective), both in transmission and distribution. Therefore, the minimum SOC is variable depending on the demand forecast.

Finally, batteries are net energy consumers, which is considered by a factor that represents the efficiency of the charging and discharging of the batteries during their operation.

4.2 Optimal batteries size and location

The nodes of the network where batteries are located are determined from the results of a contingency analysis. In the case of location of batteries in the transmission network, all possible N-1 and N-2 contingencies in the transmission network are considered. In the case of location of batteries in the distribution network, all possible N-1 contingencies are considered, taking into account the reconfiguration of the distribution network to recover part of the Demand Non-Supplied (DNS)[3] because of a loss of load event.

To be able to compare both alternatives, in both cases the same economic budget is considered for the acquisition of batteries, so that batteries are arranged in each location case in the nodes of the network that allows the reduction of DNS caused by failures in the transmission network and in the distribution network, at the lowest possible cost.

Consequently, the problem of the location of batteries is raised as an optimization problem. Equation 1 presents the objective function to maximize subject to the restriction of a maximum budget according to equation 2.

$$J = \sum_{i=x}^{N} \frac{k \cdot DNSR_i}{Cbs_i} \tag{1}$$

$$\sum_{i=x}^{N} Cbs_i \leq TB \tag{2}$$

With N being the total number of nodes that can accommodate a battery; x the corresponding node number; DNSR the reduction of DNS due to the location of a battery in the corresponding node; Cbs the cost incurred for the installation of the necessary battery to solve such DNS and TB the total budget available for the installation of batteries. In the case of batteries that solve loss of load events at both transmission and distribution, a weighting factor k is also applied.

[3] The Demand Non-Supplied is the sum of the power demanded by customers who have lost their supply at the time of the contingency. It is a parameter used by Iberdrola Distribución Eléctrica to characterize network failures with loss of supply.

4.3 Batteries dispatch optimization

To analyze the impact of batteries on the electrical system, the operation of batteries is simulated over time. Dispatch of batteries is established also by solving an optimization problem.

In this case, the problem of optimization is raised in both cases of location as a problem of variance minimization. The variance is an indicator of the dispersion of a data set. Therefore, if the variance is minimized, the fluctuation of the data set will be reduced. The variance of a set of values is determined as the mean of the squared residuals and is expressed mathematically by:

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}[x_i - \bar{X}]^2 = \frac{1}{n}\sum_{i=1}^{n} x_i^2 - \bar{X}^2 = \frac{1}{n}\sum_{i=1}^{n} x_i^2 - \left[\frac{1}{n}\sum_{i=1}^{n} x_i\right]^2 \quad (3)$$

In the case of batteries located in the transmission network, the objective of battery operation is the optimization of the load curve of the entire distribution network, in such a way that the power exchanged between the transmission network and the distribution network is reduced. By operating this way, batteries reduce the load factor of the network, which allows a greater utilization. That is to say, the objective of the operation of batteries in transmission is to minimize the variance of daily demand at the overall distribution network, which is equivalent to operating the batteries so that they are charged at off-peak or periods of low demand of the network, and discharge them when the demand is at its maximum. For the correct operation of electric batteries, a daily forecast of the load level of the distribution network must be estimated.

According to this, the objective function to be minimized daily for each battery in the case of location of batteries in transmission is presented in equation 4:

$$J = \frac{1}{N}\sum_{i=0}^{N}[Pbs_i + APbs_i + LF_i]^2 - \left[\frac{1}{N}\sum_{i=0}^{N} Pbs_i + APbs_i + LF_i\right]^2 \quad (4)$$

With N being the number of time periods to be optimized during the day (24 periods), Pbs the power of the battery in MW connected to the transmission network, APbs the sum of the powers of the rest of the batteries connected to the transmission network and LF, the expected load level in MW in the distribution network.

Meanwhile, in the case of batteries in the distribution network, the objective of the operation of batteries is the optimization of the load curve of HV/MV transformers located between the transmission network and the part of the distribution network where the batteries are located, to reduce the load variation to which transformers are exposed. By operating this way, batteries reduce the load factor of the transformer, which releases headroom in that transformer and has a positive effect on its useful life. That is to say, the objective of the operation of batteries at distribution is to minimize the variance of the daily demand at the

HV/MV transformer level. This is equivalent to operating the batteries so that they are charged at off-peak or hours of lower demand at the transformer and discharged when demand is maximum, thus decreasing the load factor, which is defined as the ratio between the peak power and the nominal power of the transformer. Similar to the case of location of batteries at transmission, for the correct operation of batteries, a daily forecast of the level of charge must be estimated, in this case for each HV/MV transformer. Therefore, it is necessary to know in advance the level of demand and generation connected to the transformer.

Consequently, the objective function to be minimized daily for each battery, in the case of location of batteries at distribution, is the same equation 4, being in this case: N the number of time periods to be optimized during the day (24 periods), Pbs the power of the battery in MW connected to a distribution network, APbs the sum of the powers of the rest of the batteries connected to the distribution network in question and LF, the expected load level in MW of the HV/MV transformer.

By optimizing either the load curve of the network, in the case of location at transmission, or the load curve of the HV/MV transformer, in the case of location at distribution, in order to reduce its variance, a combined management of demand and distributed generation in the network is also achieved, allowing for an improvement in its integration, as it is shown later in the results section.

Since the main target of using batteries is to reduce the demand not supplied in the case of loss of load events, when determining their hourly dispatch it must be ensured that the state of charge of the battery allows facing the occurrence of a loss of load event in the network at any time. Thus, the objective function defined by equation 4 must be subject to a series of restrictions regarding the power limits of the battery's charge/discharge (equation 5), the maximum state of charge (equation 6) and the minimum (equation 7). The minimum state of charge condition restriction will be defined by the minimum load required in the battery to cope with a loss of load event during a predetermined restoration or repair period. Because the requirement of the loss of load event will depend on the expected value of demand during the restoration time, the minimum demand of batteries will vary throughout the hours and days.

$$\mathrm{P}_{\max\_d} \leq \mathrm{Pbs} \leq \mathrm{P}_{\max\_c} \tag{5}$$

$$\sum_{i=0}^{N}(\mathrm{Pbs}_i) + \mathrm{SOC}_0 \cdot \mathrm{Q} \leq \mathrm{Q} \tag{6}$$

$$\sum_{i=0}^{N}(\mathrm{Pbs}_i) + \mathrm{SOC}_0 \cdot \mathrm{Q} \geq \sum_{i=0}^{M}(\mathrm{LF}_i) \tag{7}$$

Being Pmax_d the maximum discharge power in MW and Pmax_c the maximum charge power in MW, SOC_0 the initial state of charge of the battery, Q the capacity of the battery in MWh and M the repair time in hours.

The described optimization problem is solved for each hour, which allows obtaining the hourly power generated/consumed by each battery along the considered simulation horizon.

5 Study case

5.1 Study network

The study case considers the peninsular transmission network and the HV and MV distribution network in the Murcia region. The network models used have been provided by Iberdrola Distribución Eléctrica[4]. For the HV network model (Figure 3) a model of the Spanish peninsular transmission network has been used, including the equivalents of France, Portugal and Morocco, as well as the existing HV distribution network in the Murcia region. This model presents the operating situation of the transmission network for the winter peak of 2015, so that generation and demand for the days studied in 2014 have been scaled up from the information published by REE[5] [19].

Figure 3. Peninsular HV network modelled in the study

The MV network model of Murcia includes each HV/MV transformer together with its associated MV network, including the load from MV customer, the load of secondary substations (SS) to LV and the connected distributed generation. This set of elements is called area in the present study by similarity with the treatment in the simulation software used. Effectively, each MV distribution network analyzed is made of a certain number of areas. These areas are connected to each other through the HV network feeding them. Figure 4 shows part of the MV network model for the Murcia area obtained from the PSS/E software. Each color corresponds to an area of the network.

[4] Iberdrola Distribución Eléctrica distributes energy to more than 11 million customers in the regions of La Rioja, Navarra, the Basque Country, the Valencian Community, Murcia, most of Castilla y León, and some areas of Madrid, Castilla-La Mancha and Extremadura. In 2016 it distributed a total of 92308 GWh with a peak demand of 14 GW . https://www.iberdroladistribucion.es/

[5] Red Eléctrica de España (REE) is the transmission network owner and system operator of the Spanish

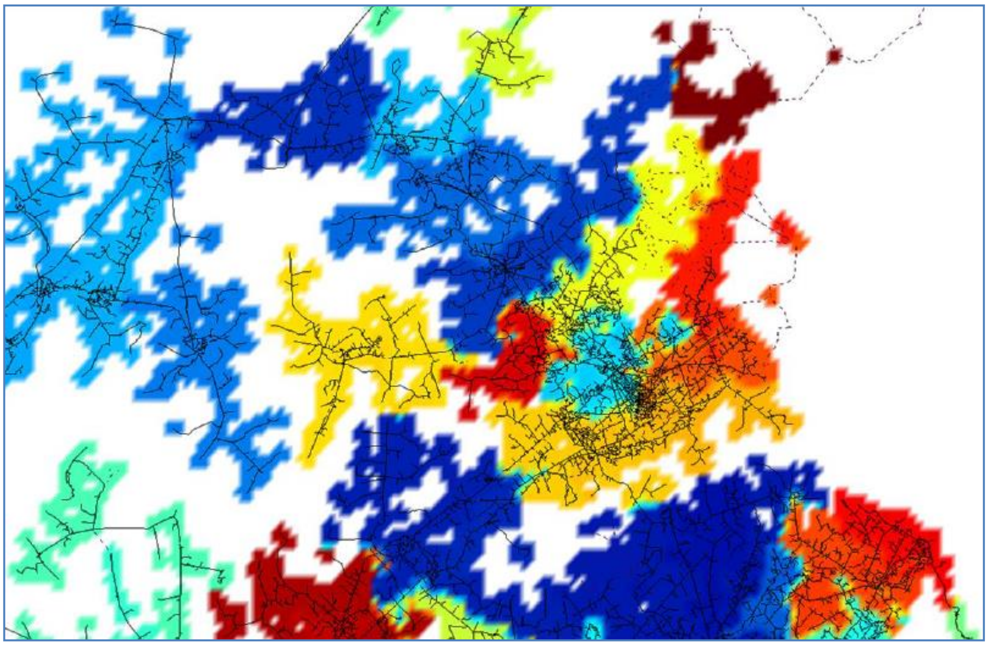


Figure 4. MV network model in the Murcia region

The number of elements that comprise the PSS/E models of the transmission, HV distribution and MV distribution networks is shown in Table 1. For the development of the study, both networks have been linked to obtain a single network model.

NETWORK	Nº Networks	Nodes	Generators	Loads	Transf.	Lines
Peninsular transmission and HV distribution	1	2674	655	989	1243	3788
MV distribution in Murcia	90	31721	15388	15388	94	33327

Table 1. Number of elements in the network model

Table 2 shows demand and generation existing in the distribution network of Murcia during winter and summer peaks for the starting situation corresponding to year 2014.

Demand (MW)	Winter peak 2014	Summer peak 2014
Customers	992	994
Electric vehicles	0	0
MV total demand	992	994
Distributed generation	235	294
PV self-consumption	0	0
MV total generation	235	294

Table 2. Demand and generation in the distribution network in Murcia for the base case

electrical system. http://www.ree.es

5.2 2025 scenario definition

For the assessment of the impact of the installation of batteries, the year of study has been established in 2025. To obtain the demand and generation scenario for the Murcia area in 2025, the following considerations have been applied.

The demand of the distribution customers has been determined from the hourly demand curve of the Murcia region for the year 2014, affected by an annual growth factor of 1.7% (including EVs), according to the most conservative demand growth assumption considered by REE in the planning of the transmission network [20].

For the estimation of the demand corresponding to the electric vehicle in the year 2025, the results of a study by Deloitte [21] have been taken into consideration, where 2 million EVs are deemed to be necessary in 2025 to meet the decarbonization objectives of the transportation sector in the Spanish State. Currently, the automobile fleet in the Murcia region is approximately 1 million vehicles, which is 3.1% of the Spanish automobile fleet [22]. Therefore, an EV penetration in Murcia of 62,000 vehicles has been assumed. Meanwhile, recent studies show that the average of daily kilometers made by an EV is 34.3 km [23]. Taking into account a consumption of 0.2 kWh/km, a load power of 3.7 kW with a load efficiency of 85%, the global daily demand associated with charging the electric vehicles in 2025 in Murcia has been estimated at 500.4 MWh, which represents an equivalent daily demand by EV of 8.07 kWh. The hourly distribution of the daily demand of the EV has been determined considering conservatively a lower off-peak rate with the EV charging during night hours. Figure 5 shows the equivalent demand per EV connected to the distribution network. The global energy demand due to EV charging, obtained as described, has been distributed among the different low voltage secondary substations proportionally to the number of customers of the secondary substation with respect to the total number of customers.

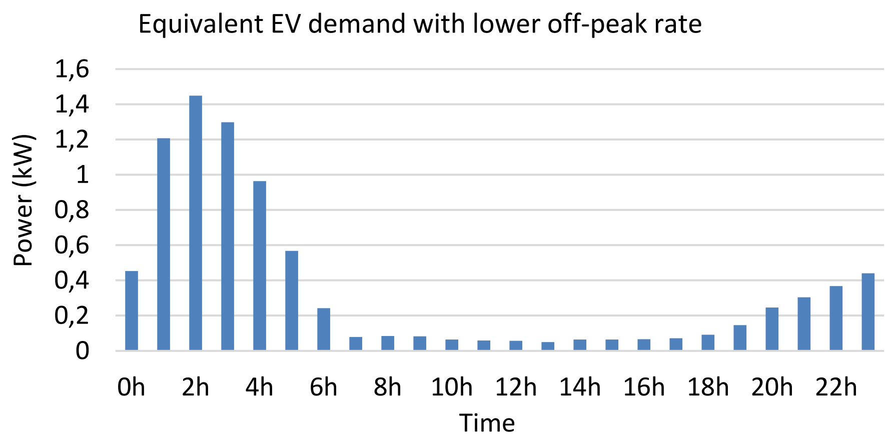


Figure 5. Equivalent demand per EV connected to the distribution network

With regard to generation, a future generation scenario with a reasonable level of renewable penetration has been defined. Thus, in relation to large-scale generation, this scenario incorporates future renewable generation projects that have passed the "acceptability process" of REE.

Additionally, the developed generation scenario considers the growth of photovoltaic self-consumption facilities. In particular, a level of adoption of self-consumption equal to 20% of the annual energy consumed by the customers of the distribution network has been adopted, slightly concentrated. The methodology applied for the sizing and location of self-consumption facilities is described in detail in [18]. According to this methodology, the concentration of self-consumption facilities is carried out at the area level and as a function of the load per distribution line length (MWh/km). Thus, it is considered that the areas with lower demand/km are rural areas, with greater availability of space to locate photovoltaic generation, and those with higher demand/km are considered urban, with a greater space limitation. In the case of a light concentration, 63% of self-consumption is located in 50% of the areas with lower load density, that is, it is slightly concentrated in rural areas. Figure 6 shows the geographical distribution of photovoltaic self-consumption facilities considered in the study.

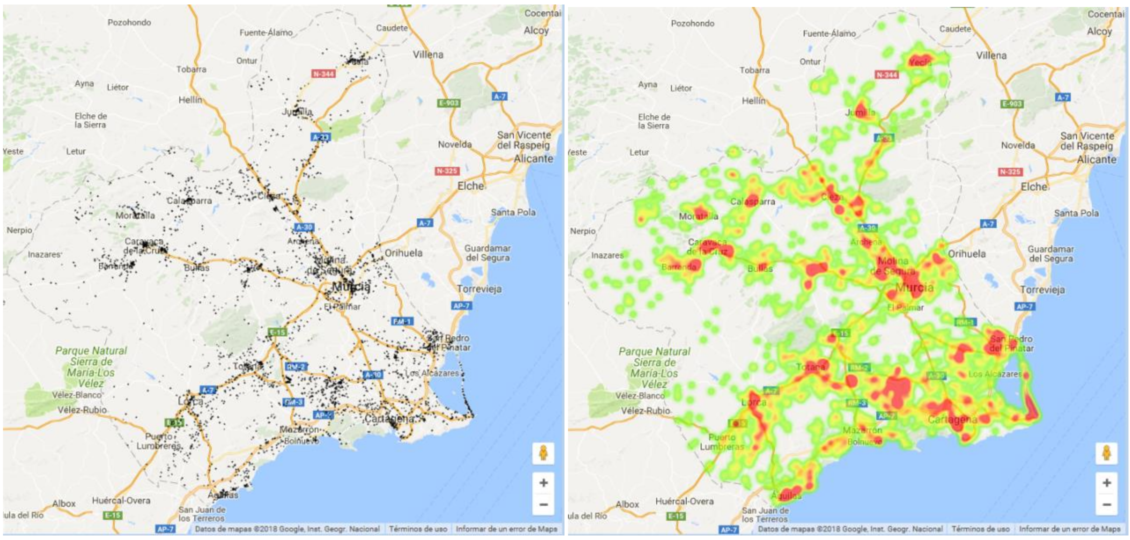


Figure 6. Geographical distribution of photovoltaic self-consumption facilities in the 2025 scenario

The hourly power generated by the photovoltaic installations has been calculated from the hourly irradiation recorded during 2014. This information has been obtained from the PVGIS[6] database, using the information of the closest measurement station to the photovoltaic generator, taking into account the geographical coordinates of the customer with self-consumption. Figure 7 shows the average hourly radiation for the month of July in Molina de Segura[7].

[6] PVGIS has been developed for more than 10 years in the JRC of the European Commission, in Ispra, Italy. The focus of PVGIS is research into the evaluation of solar resources, studies of photovoltaic performance (PV) and the dissemination of knowledge and data on solar radiation and photovoltaic performance. Data available in: http://re.jrc.ec.europa.eu/pvgis.html

[7] Molina de Segura is a city of 70344 inhabitants that is located at a distance of 14 km from Murcia Capital, which has a population of 441,000 inhabitants.

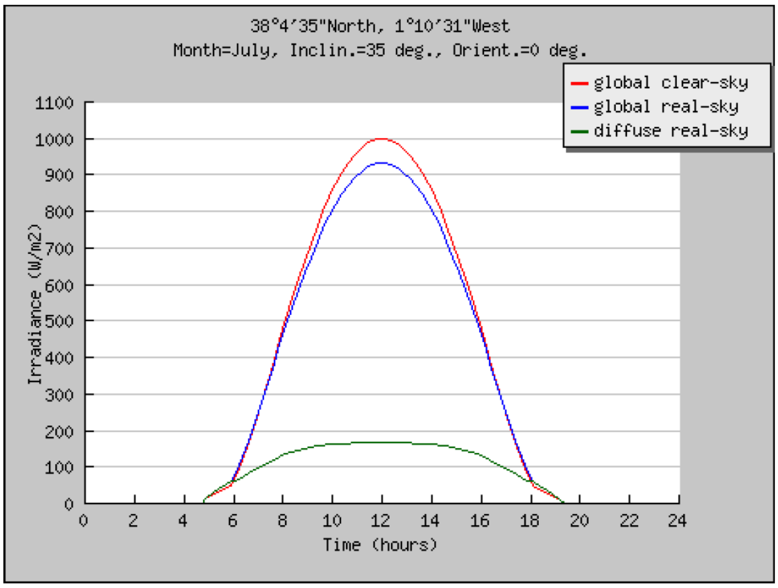


Figure 7. Average hourly radiation for the month of July

The demand and generation situation corresponding to the summer and winter peaks in the future scenario is shown in Table 3 compared to the initial situation.

Demand MW	Winter peak 2025	∆ 2025/2014	Summer peak 2025	∆ 2025/2014
Customers	1172		1185	
Electric vehicles	18		4	
MV total demand	1190	20%	1188	20%
Distributed generation	235		294	
PV self-consumption	0		468	
MV total generation	235	0%	762	159%

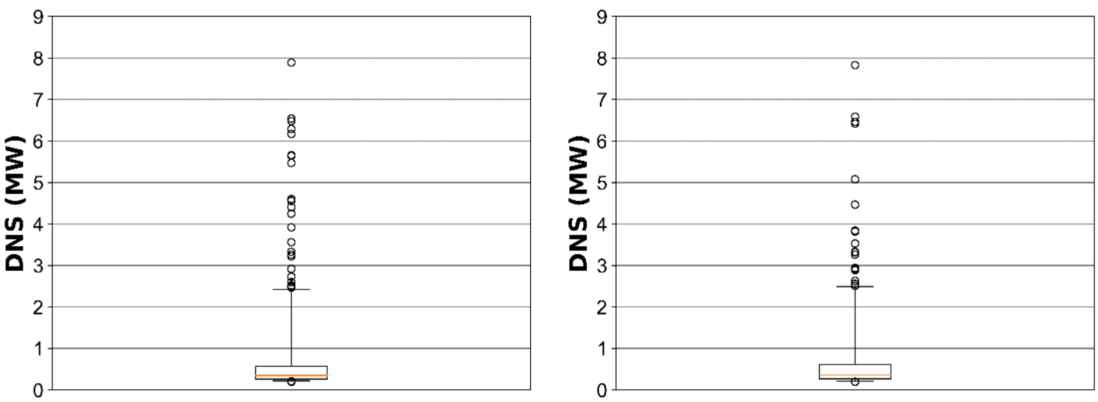
Table 3. Demand and generation in the distribution network in Murcia for the 2025 scenario

5.3 Contingency analysis for 2025

This study has considered that the main objective of the installation of batteries in the network is the improvement of the quality of supply, by providing support during loss of load events in the transmission or distribution network supplying the necessary power to cover the affected demand during the duration of the loss of load event. For this reason, a contingency analysis has been carried out in the scenario corresponding to 2025 in order to quantify the DNS because of the occurrence of incidents in the transmission network and in the distribution network. The situation considered for carrying out the contingency analysis is that corresponding to the winter and summer peaks because they are the most unfavorable situations from the point of view of the DNS.

In the case of the MV distribution network, the N-1 criterion has been applied in the contingency analysis, considering both the failure of the supply line to each node of the distribution network and the failure of the MV bus in the distribution substation. To do this, a topological sweep is carried out along the lines, identifying the network nodes where power failures need to be analyzed. For example, if there are several consecutive nodes, it suffices to analyze the upstream node. The contingency analysis considers the possibility of reconfiguring the distribution network to provide supply to the affected circuit from another circuit/transformer, identifying the alternative operations that allow obtaining a feasible solution without overloads or overvoltages and recovering the highest possible load, thereby reducing the DSN affected by the loss of load event. As a last measure, load-shedding operations are carried out to try to resolve the contingency and supply the highest possible demand.

As a result of the contingency analysis in the MV distribution network during the winter peak, 529 N-1 outages have been identified producing a total of 354.95 MW of DNS. In the case of the summer peak 418 N-1 outages have been identified, leading to 285.53 MW of DNS. Figure 8 shows the range of variation of DNS in the contingency analysis performed for winter and summer peak situations. In both cases it can be observed that the 25 and 75 percentiles are of the order of 0.26 MW and 0.6 MW, respectively, and that only 5% of the loss of load events produces a DNS value greater than 2.5 MW.



(a) Winter peak (b) Summer peak

Figure 8. DNS variation range without batteries

Additionally, figure 9 shows the geographical distribution of loss of load events in the distribution network during winter peak, highlighting that the highest number of incidents is located in the northwest area of the province.

Figure 9. Geographical location of faults in the distribution network (2025 winter peak)

Regarding the transmission network, according to the Energy Planning published by the Ministry of Industry, Energy and Tourism [20], there is currently a mesh deficit at 220 kV in Murcia and Alicante that leads to a high risk situation of loss of supply, as the 220 kV coastal interconnector middle nodes are insufficiently meshed. Thus, to estimate the DNS caused by loss of load events in the transmission network, the worst N-2 outage at 220 kV (consisting on the loss of the 220 kV coastal interconnector) has been considered in the study (Figure 10) due to the simultaneous failure of the 220 kV San Miguel de Salinas phase shifting transformer and the interconnector between the 220 kV Fausita and Hoya Morena nodes.

Figure 10. 220kV Murcia interconnector affected by the N-2 outage

This situation leaves that part of the interconnector isolated and it must be fed from the 66 kV system, producing a voltage collapse at that and lower voltage levels, and the loss of several substations (Figure 11). This outage implies the need to shed load in Murcia and Alicante to avoid voltage collapse. The value of DNS in the MV distribution network of Murcia is 51.6 MW at winter peak and 44.4 MW at summer peak.

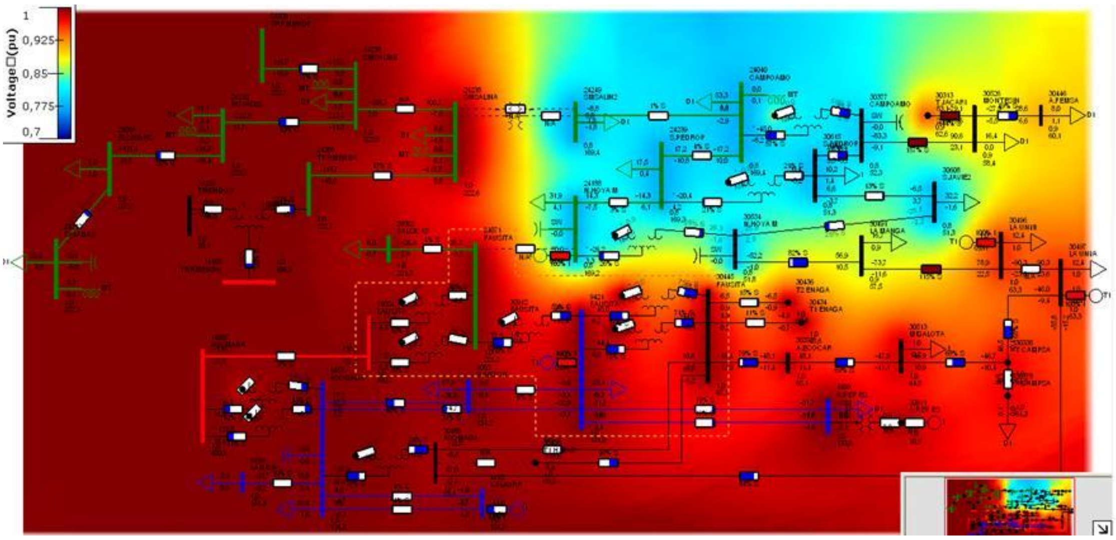


Figure 11. Voltages map in the transmission network after N-2 outage

6 Results

6.1 Optimal size and location of batteries

Based on the results of the contingency analysis carried out in the 2025 scenario, the optimal size and location of batteries has been determined following the methodology described in section 4.2, to minimize the DNS due to loss of load events in the transmission and distribution networks, and considering the two possible cases of location of batteries:

- In the transmission network
- In the distribution network

In order to compare both alternatives, it has been assumed in the study that the available budget for the installation of batteries by 2025 is the same in both cases. The amount considered must be realistic so that it does not result in a level of investment in new assets higher than that allowed by the regulator. Additionally, it must have a limited value, so that not all the possible identified incidents are resolved and make possible to identify the greater or smaller benefit obtained by installing batteries at every alternative location.

Following the above criteria, the available budget for the installation of batteries has been determined based on the assumption that the annual budget for investment in the region of Murcia is of the order of 8% of a total investment budget of 500 Mill. € per year. Likewise, it has been assumed that 50% of this budget is used to modernize the network, with the remaining 50% being used for conventional development and R & D. Considering a favorable scenario in which up to 20% of that amount is used to make investments in new network installations, through the application of new technologies such as battery storage, an annual amount of € 8 Mill. € is obtained. This value is deemed reasonable for the purchase of batteries, which represents a cumulative total of 96 Mill. € in the year 2025. Hence, it has been considered in the study that the accumulated investment level for batteries in 2025 is 100 Mill. €.

Regarding the cost of batteries, according to the Lazard study published in December 2016 [21], the initial total cost of installing lithium batteries depends on its application:

- $440 – $1045/kWh for applications in transmission, considering a standard battery of 100 MW/800 MWh.
- $501 – $1045/kWh for applications in distribution substations, considering a standard battery of 4 MW/16 MWh.
- $537 – $1089/kWh for applications in distribution feeders, considering a standard battery of 0.5 MW/1.5 MWh.

The difference in the cost of the battery is explained by the different power/energy ratio. The higher the ratio, the lower the weight of the power electronics compared to the batteries. According to the Lazard study, an average annual reduction coefficient of 11% can be applied to the previous prices. Thus, considering an annual cost reduction of 11% until 2025, the average cost of batteries in 2025 can be estimated for each application by:

$$\mathrm{C}_{\mathrm{m},2025} = \mathrm{C}_{\mathrm{m},2016} \cdot (1 - 0.11)^{10} \tag{8}$$

Considering an exchange rate of 1.09 €/$ the average battery unit cost by 2025 expressed in €/kWh results in:

- 212.4 €/kWh for applications in transmission, considering a standard battery of 100 MW/800 MWh.
- 221.1 €/kWh for applications in distribution substations, considering a standard battery of 4 MW/16 MWh.
- 232.6 €/kWh for applications in distribution feeders, considering a standard battery of 0.5 MW/1.5 MWh.

The main objective of the batteries considered in this study is to solve loss of load events originated in the transmission or distribution network, so the value of DNS originated because of the loss of load event determines the power of the battery to install in a network node to solve the incident. To determine the location and size of the batteries, the results obtained in the contingency analysis are considered so that the DNS associated with every loss of load event can be used to determine the energy of the battery needed to solve it.

The time during which the battery must supply power, or what is the same, the power/energy ratio, is determined by the duration of the fault. The average duration of every incident corresponds to the average time of resolution of the fault, being higher in the case of faults in the transmission network compared to the distribution network, and in the case of faults in underground cables with respect to failures in overhead lines.

In the case of incidents in the distribution network, the following values have been considered in this study for the average time of resolution of the incident during which the battery must be able to supply the DNS. These values have been provided by Iberdrola Distribución Eléctrica:

- Incidents in MV distribution overhead lines: 3 hours
- Incidents in MV distribution underground cables: 9 hours

For the case of incidents in transmission overhead lines, in the absence of any other information, a mean time of resolution of 9 hours has been adopted in a simplified approach, which is the same order of magnitude as in the case of incidents in HV distribution overhead lines, according to information provided by Iberdrola Distribución Eléctrica. Accordingly, the power/energy ratio of the battery to be installed to solve a loss of load event in a distribution overhead line is 1:3, while for the resolution of a loss of load event in an underground distribution cable or in a transmission overhead line it is 1:9.

Taking into account the above, the cost of batteries considered in the study has been as follows, depending on the type of node in which the loss of load event that is intended to be resolved with the battery is originated:

- 212.4 €/kWh for transmission overhead lines
- 212.4 €/kWh for distribution underground cables
- 232.6 €/kWh for distribution overhead lines

The budget limitation prevents the resolution of all loss of load events and makes necessary to locate the batteries in those locations that allow optimizing the available budget, taking into account the unit cost of the battery depending on its application. Therefore, taking into account the battery power required to restore supplies under every loss of load event, the power/energy ratio of the battery and the unit cost of the battery according to the type of failure, the battery location is optimized for loss of load events in both location cases (in the transmission or the distribution networks), selecting the most effective battery size and the most efficient location facing all the loss of load events under consideration, that is, those batteries that allow to restore more DNS with lower cost or that allow obtaining a higher DNS/battery cost ratio, until the budget is exhausted.

The result obtained shows that the optimum set of batteries to be installed in the distribution network to cope with loss of load events would consist of 63 batteries with an installed power of 76.5 MW and an energy storage capacity of 433.5 MWh, with the total cost of € 99.81 million. The location of batteries has been optimized for the case of the winter peak since the value of DNS is higher than that obtained for the summer peak. In addition, a greater weight has been given to those batteries that, on top of resolving loss of load events in the distribution network, can also contribute to reduce the DNS due to losses in the transmission network.

Figure 12 shows the number of batteries obtained in each power range as a result of the optimization process. Batteries are installed in 44 out of the 90 MV areas available in the network model. Likewise, as it is shown in Figure 13, in most occasions a single battery is enough, with an average power of the order or less than 1 MW.

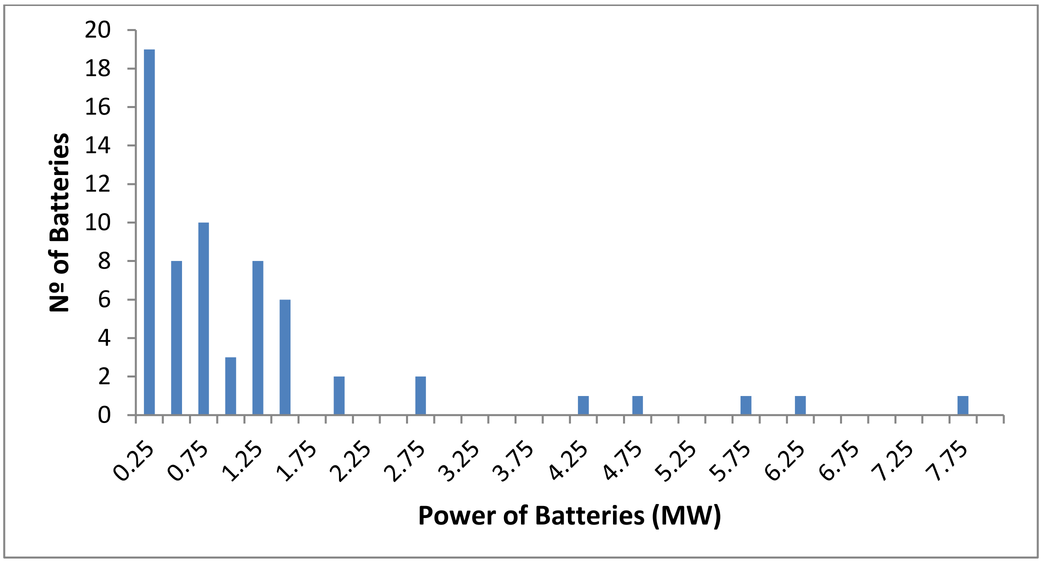


Figure 12. Number and power of batteries located in distribution

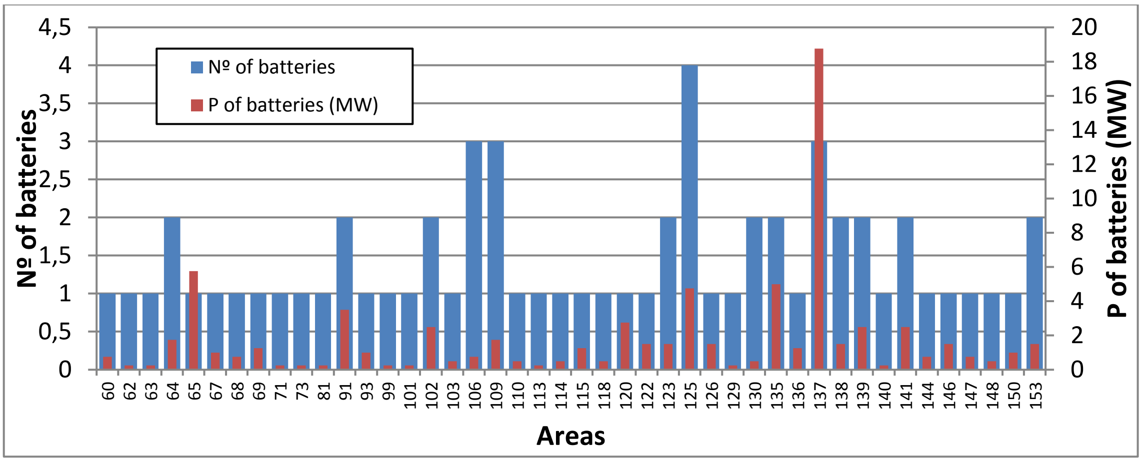


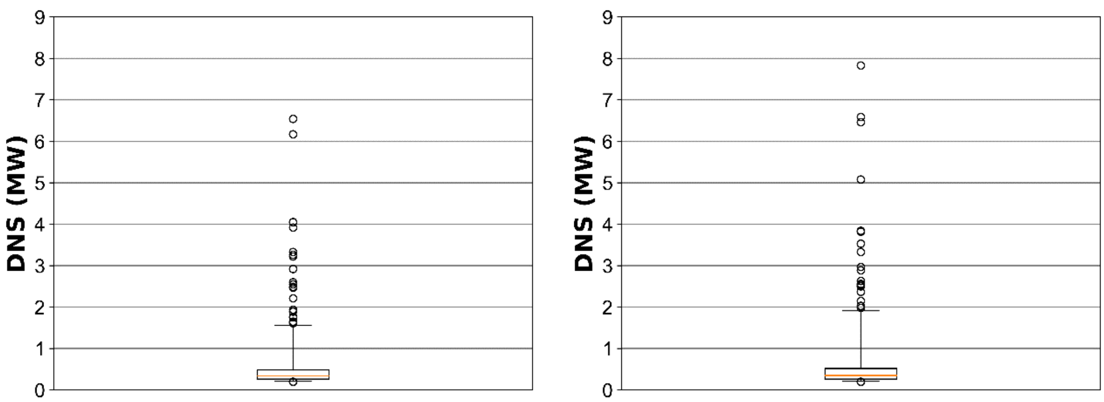
Figure 13. Number of batteries and batteries installed power per MV area

In contrast, the budget available for batteries would allow the installation of 2 batteries in the transmission network, of 30.5 MW and 21.5 MW respectively, located in the 220 kV Hoya Morena and the 220 kV San Pedro del Pinatar nodes, for the management of transmission outages with a total installed power of 52 MW and an energy storage capacity of 468 MWh, the total cost in this case being 99.4 Mill. €.

6.2 Impact of batteries in the contingency analysis

The resolution of the contingency analysis in the 2025 scenario considering the presence of batteries allows the assessment of their impact in each location case, compared to the situation without batteries.

For the installation of batteries in the distribution network, the contingency analysis in the distribution network for the winter peak shows 460 N-1 outages with a DNS of 251.86 MW. When carrying out the contingency analysis in distribution for the summer peak, with batteries installed in the distribution network, it results in 386 N-1 outages with a DNS value of 234.1 MW. Figure 14 shows the change range of DNS in the contingency analysis performed for the winter and summer peaks. It can be observed that in both cases the 25^{th} and 75^{th} percentiles are of the order of 0.26 MW and 0.5 MW respectively. Only 5% of the loss of load events produces a DNS higher than 1.56 MW during the winter peak and higher than 1.96 MW during the summer peak.



(a) Winter peak (b) Summer peak

Figure 14. DNS Change range with batteries installed in the distribution network

In this way, the installation of batteries in the distribution network (total storage: 76.5 MW/433.5 MWh) has a positive effect on loss of load events in the distribution network, reducing the number of incidents and the global DNS value and by loss of load event, compared to the situation without batteries.

Taking into account the type of incident (overhead or underground) and the duration of each failure, it is also possible to assess the effect of the batteries in terms of Energy Not Supplied (ENS)[8]. The improvement obtained for loss of load events in the distribution network, in the case of placing batteries in the distribution network compared to the situation without batteries is as included below (Figure 15):

- Reduction of 103.1 MW of DNS and 897.8 MWh of ENS during the winter peak
- Reduction of 51.4 MW of DNS and 448.2 MWh of ENS during the summer peak

Moreover, the location of batteries in the distribution network has a positive effect in loss of load events in the transmission network. Carrying out the analysis of loss of load events in the

[8] The Energy Not Supplied (ENS) is defined as the energy that a distribution customer has not received during the duration of the loss of load event. In this study, this energy has been calculated deterministically; assuming that the probability of the loss of load event occurring is 1 and that during the entire duration of the failure the power consumed is equal to the one before the failure.

transmission network, considering batteries installed in the distribution network, the results are as follows (Figure 15):

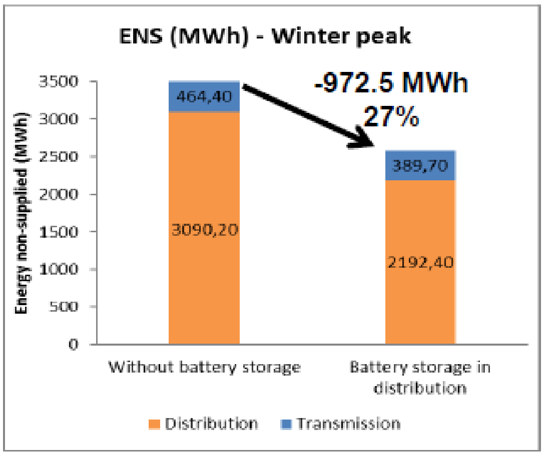
- Reduction of 8.3 MW of DNS and 74.7 MWh of ENS during both the winter and the summer peaks

On the other hand, if batteries are located in the transmission network (total storage: 52 MW/468 MWh), their effect in loss of load events in the distribution network and in the transmission network is the one indicated below (Figure 15):

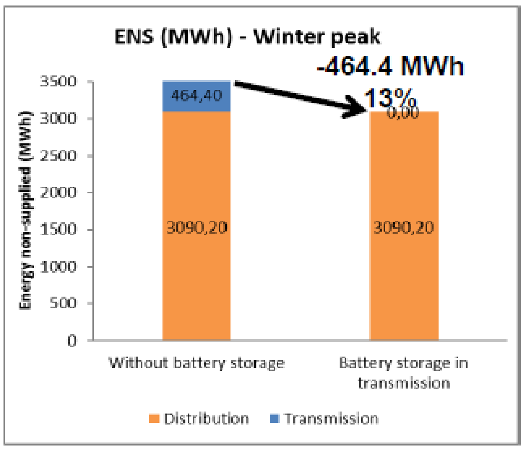
- For loss of load events in the distribution network there is no improvement. Although batteries have been located in the two transmission network locations where they are effective for the N-2 outage, for any loss of load event in the distribution network they do not support to recover part of demand. Their location in different points of the transmission network does not support loss of load events in distribution either.

- The problem caused by loss of load events in the transmission network is eliminated:
    - Reduction of 51.6 MW of DNS and 464.4 MWh of ENS during the winter peak
    - Reduction of 44.4 MW of DNS and 399.6 MWh of ENS during the summer peak

63 batteries in distribution
76.5 MW / 433.5 MWh



2 batteries in transmission
52 MW / 468 MWh



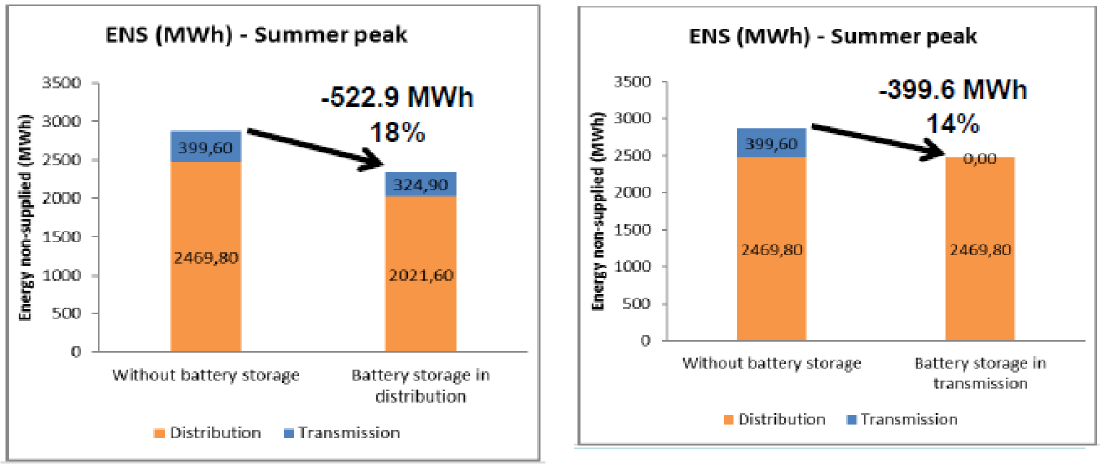


Figure 15. Impact of batteries in the transmission and distribution networks during loss of load events

Based on these results, it can be concluded that the efficiency of batteries during loss of load events in the transmission and distribution networks is much greater if they are located in the distribution network, since they provide a greater DNS reduction in case of loss of load events in the distribution network, and additionally, they provide support during loss of load events in the transmission network. On the contrary, the location of batteries in the transmission network allows the resolution of loss of load events only in the transmission network and the reduction of the DNS is lower for the same economic budget, while not providing any support for loss of load events in the distribution network.

6.3 Impact on the operation of batteries

Taking into account the optimal location of batteries determined for each case of location, the operation of the installed batteries over a whole year has been simulated in order to evaluate their effect on the operation of the system, comparing the result obtained with that of the simulation of the system without the installation of batteries.

Year 2014 has been considered as the base year for the simulation. For this year, eight days have been considered as type days: one working day and another holiday for each of the four seasons of the year. These type days correspond to those days of each season that have a demand more similar to the average and have been adopted as representatives of the situation of the MV network throughout that period.

For each of the 24 hours of the day of the eight days considered, Iberdrola has provided the MV network model of Murcia and the average hourly demand of each customer of the MV network in Murcia. This information is available in the form of a RAW[9] file for each hour of the

[9] RAW is a data format to represent electricity power systems in PSS/E software from the company Siemens

8 days considered. The model of the MV network of each type day has been completed with the network model corresponding to the transmission and HV distribution networks.

Additionally, Iberdrola has provided hourly information of demand and generation of the special regime by voltage level existing in Murcia during 2014. Based on this information and the cases corresponding to the different types of days, PSS/E cases have been created for each hour of the simulation period considered in the study, corresponding to year 2025. To achieve this, the cases corresponding to the standard days have been modified, scaling the demand and generation at MV to the real hourly value provided by Iberdrola, also applying the growth coefficient to obtain the 2025 scenario. Similarly, national demand has been scaled to the real hourly value obtained during 2014, according to information published by REE, also affected by the corresponding growth coefficient.

Lastly, the photovoltaic generation corresponding to new installations and self-consumption facilities has been calculated from the hourly irradiation values during 2014, applying the procedure described in section 5.2.

For each hour of the day throughout each day of the simulation period, the use of all installed batteries is optimized by applying the following considerations:

- In the case of installation of batteries in distribution, the load curve of the HV/MV transformer that feeds the part of the network where the batteries are located is optimized.
- In the case of installation of batteries in transmission, the global load curve of the Murcia network is optimized to reduce the power exchanged between the transmission network and the distribution network.

In both cases, maintaining a certain level of charge in the batteries is considered as an operational restriction so that the battery can supply the expected load level during the duration of the loss of load event. For this, it is necessary to make a prediction of the load curve of the HV/MV transformers or of the overall load curve of Murcia, depending on whether the batteries are installed in the distribution network or in the transmission network. A two-day forecast horizon has been considered, to be able to estimate the battery's energy in order to cope with the occurrence of loss of load events in the last hours of the day, which implies the need to estimate the load curve in the first hours of the next day. In the optimization process it has been considered in a simplified way that the load curve corresponding to the following two days is known. Finally, in the optimization of the operation of batteries it has been considered that the performance of the battery charging and discharging process is 93.8%, that is, an overall efficiency of the battery for a full charge and discharge cycle is considered 88%.

Both the calculation of the load flow and the subsequent analysis of the data have been automated using Python scripts, for PSS/E, and VBA macros, for Excel. The IBM ILOG CPLEX optimization software in the Python environment has been used for the planning and resolution of the battery operation optimization problem.

Figure 16 shows the effect of batteries on the total power exchange of the Murcia region during the period from August 1st to 7th 2025. A negative value of power exchanged represents a demand higher than the existing generation and vice versa. As noted, the installation of batteries reduces the exchange of power and, consequently, the variation of the load curve, although the effect is not very appreciable due to the reduced value of the installed power in batteries compared to the demand of Murcia.

Figure 17 shows the total power generated by batteries in transmission and distribution, observing that the range of power variation of the batteries is quite similar in both cases. The different temporal evolution is due to the different strategy applied in the operation of the batteries, since the batteries in transmission are operated in such a way that the exchange of energy with distribution is reduced; while the operation of the batteries in distribution is aimed at optimizing the load curve of the distribution transformers. Thus, it is observed that the operation of batteries in transmission corresponds to the variation of the power exchange represented in Figure 17.

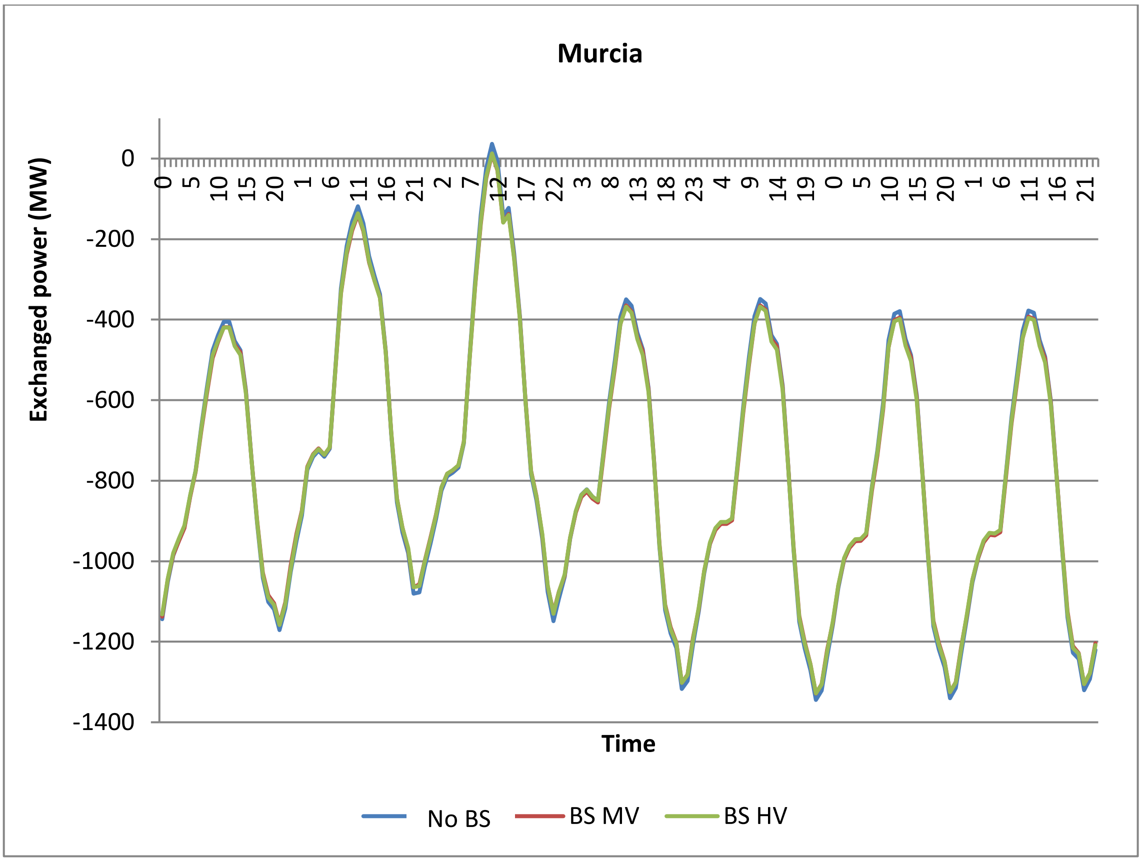


Figure 16. Power exchange between Murcia and the rest of the system (from 1st to 7th August 2025)

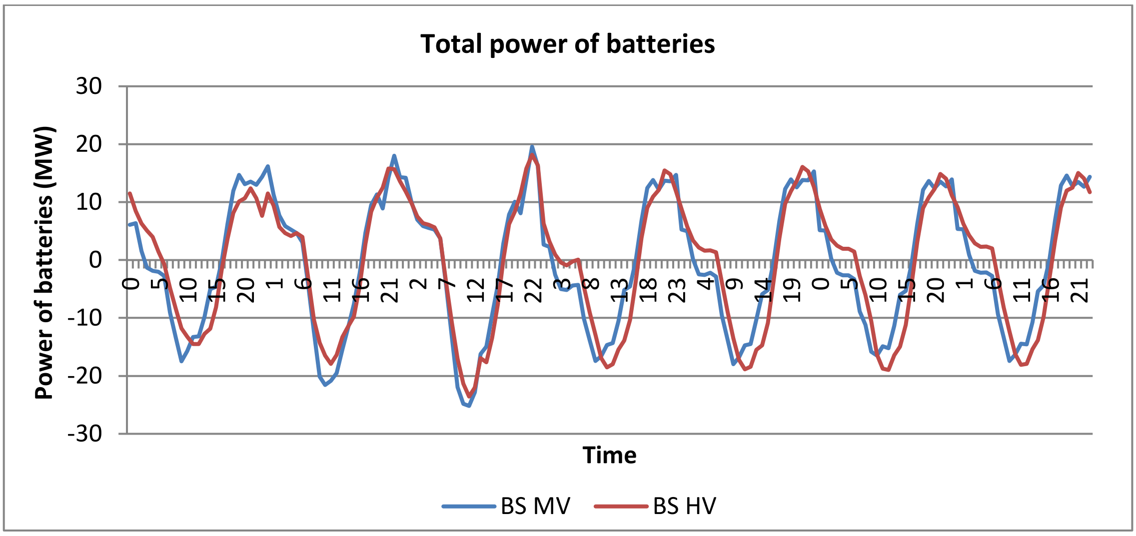


Figure 17. Total power of batteries (from 1st to 7th August 2025)

Next, the effect of the installation of batteries in transmission or distribution in an area of the medium voltage network of Murcia is studied. Specifically, Figure 18 shows the result obtained for a week in August 2025 for the power exchanged by area 137. In this area, in the case of location of batteries in distribution, a total of 3 batteries with a total power of 18.75 MW are installed. As it is observed, the optimization of the operation of batteries allows the reduction of the power exchange, and therefore smoothing the load curve of the HV/MV transformer that feeds the area of the network in which the batteries are located. In contrast, the location of batteries in transmission has no effect on the load curve of this area of the distribution network compared to the situation without batteries, since in the case of location in transmission the batteries are far from this part of the distribution network.

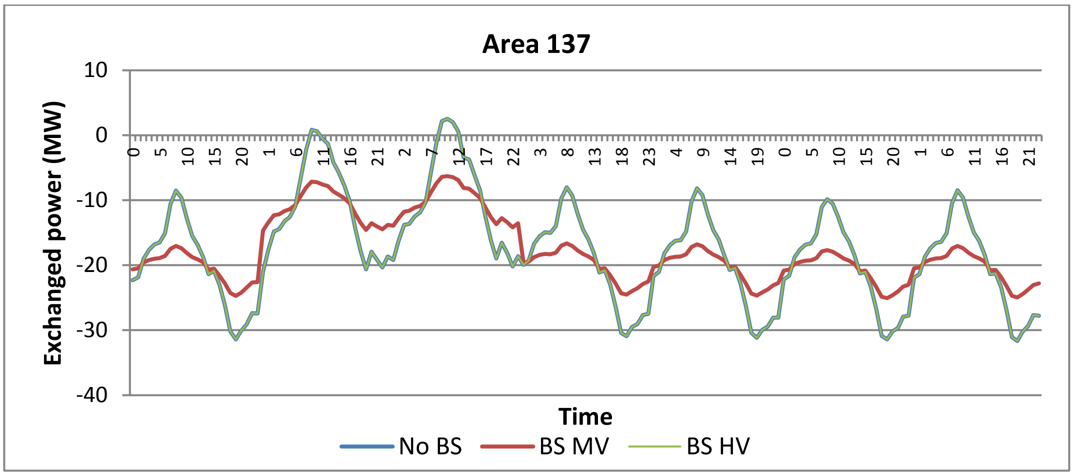


Figure 18. Exchanged power in area 137 (from 1st to 7th August 2025)

The load curve of the HV/MV transformers is obtained as a result of the difference between the demand and generation of energy in each part of the network, as shown in Figure 19.

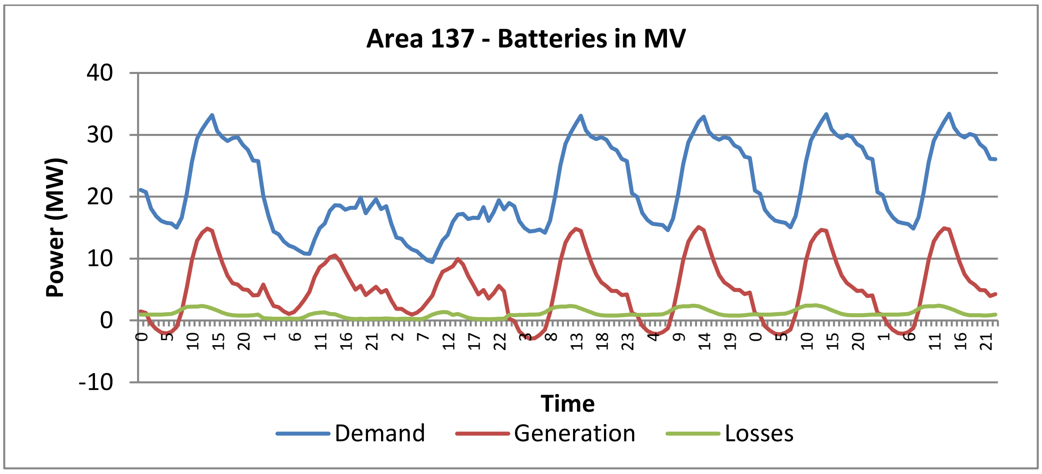


Figure 19. Demand, generation and losses in the area 137 (from 1st August to 7th August 2025)

The generation in the MV distribution network is due to photovoltaic self-consumption installations and the installation of batteries. According to Figure 20, the batteries are charged mainly by the photovoltaic generation from the self-consumption facilities, returning the stored energy later, in order to obtain a smoothing of the load curve of the transformer.

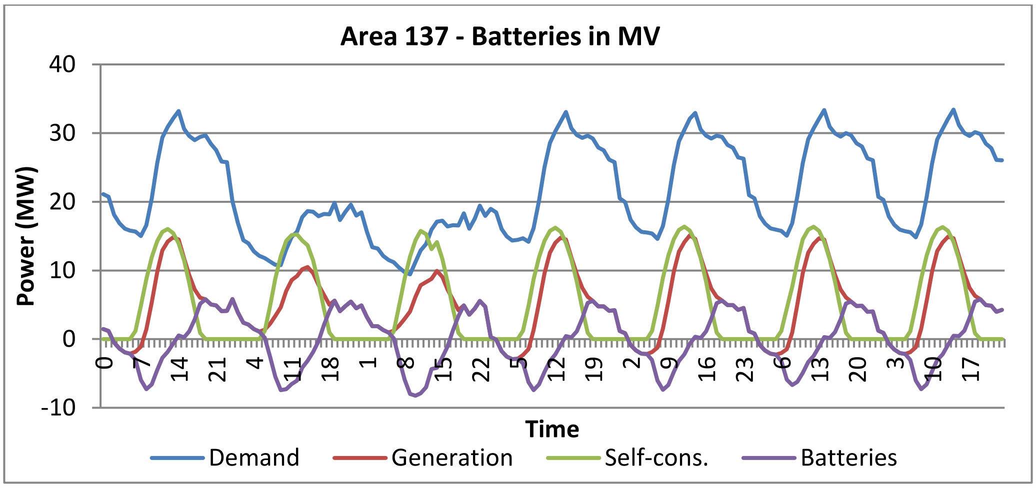


Figure 20. Demand, generation, self-consumption and batteries profile in area 137 (from 1st August to 7th August 2025)

Figure 21 shows the operation of one of the batteries located in area 137 over two consecutive days. As observed, the battery stores energy during the central hours of the day, increasing its charge level, and discharges during the night, returning stored energy to the system. The power stored/supplied by the battery in each hour is determined in such a way that the load curve of the HV/MV transformer is minimized.

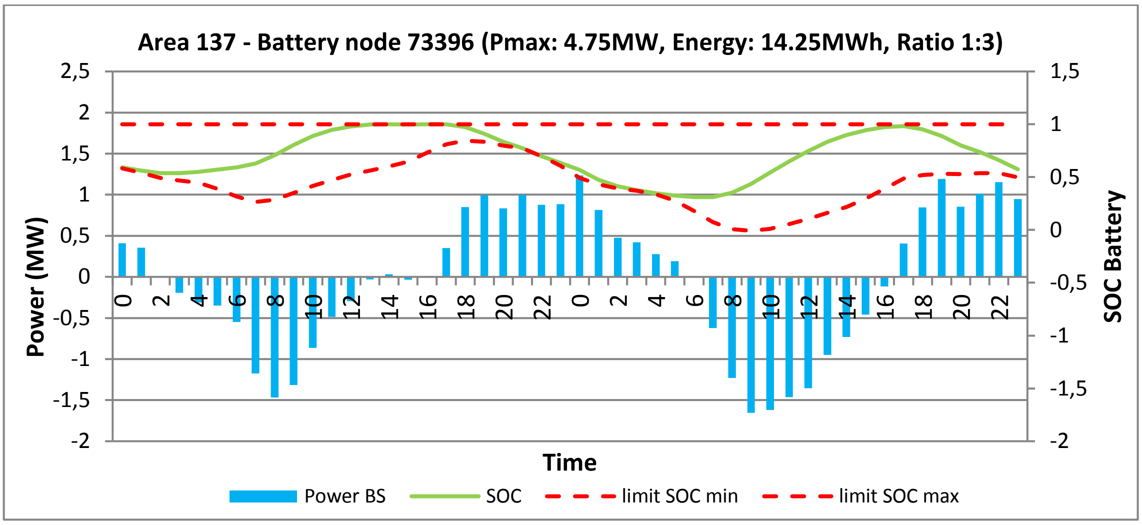


Figure 21. Power and state of charge in the battery located in node 73396 in the area 137 (from 1st August to 2nd August 2025)

The optimization ensures an adequate energy level of the battery to respond to contingencies by applying a minimum SOC (state of charge) restriction that takes into account the expected load curve in the next 3 hours for batteries located in overhead lines and 9 hours for underground ones. The state of charge of the battery is maintained between a maximum limit and a minimum limit. The maximum SOC limit is equal to the unit, since the battery cannot be charged above its maximum capacity. In contrast, the minimum SOC limit represents the minimum load level necessary to cope with the occurrence of a loss of load event. Thus, Figure 21 shows that there are hours for which the limit of the minimum SOC is equal to zero, which corresponds to a situation in which the demand is covered by the existing generation, so that the load of the transformer is nil.

Figure 22 shows the net demand of the area for the same period, calculated as the difference between demand and generation in the area, with and without batteries, together with the power generated/consumed by the batteries located in that area, in the case of batteries in distribution. It can be observed that the presence of batteries produces the desired effect of smoothing the load curve of the area.

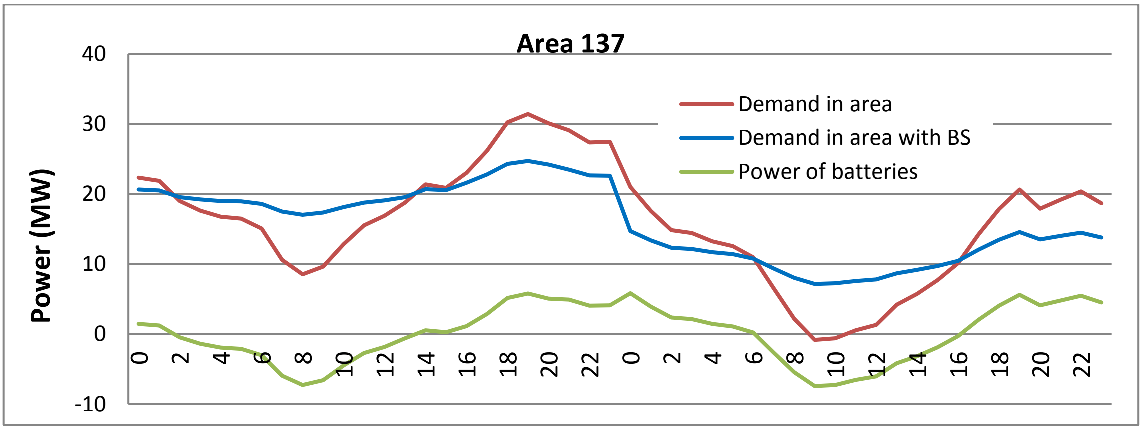


Figure 22. Effect of the dispatch of batteries in distribution: power demand in transformer in area 137 (from 1st August to 2nd August 2025)

On the other hand, the installation of batteries in the high voltage busbar of HV/MV substations to support loss of load events in the transmission network affects mainly the transmission network by modifying the power exchange with the transmission network through the nodes in which the batteries are connected. Thus, for example, in the case of having a 30.5 MW battery in the 220 kV Hoya Morena bus, the net demand of the bus is reduced by an amount equal to the power generated by the battery.

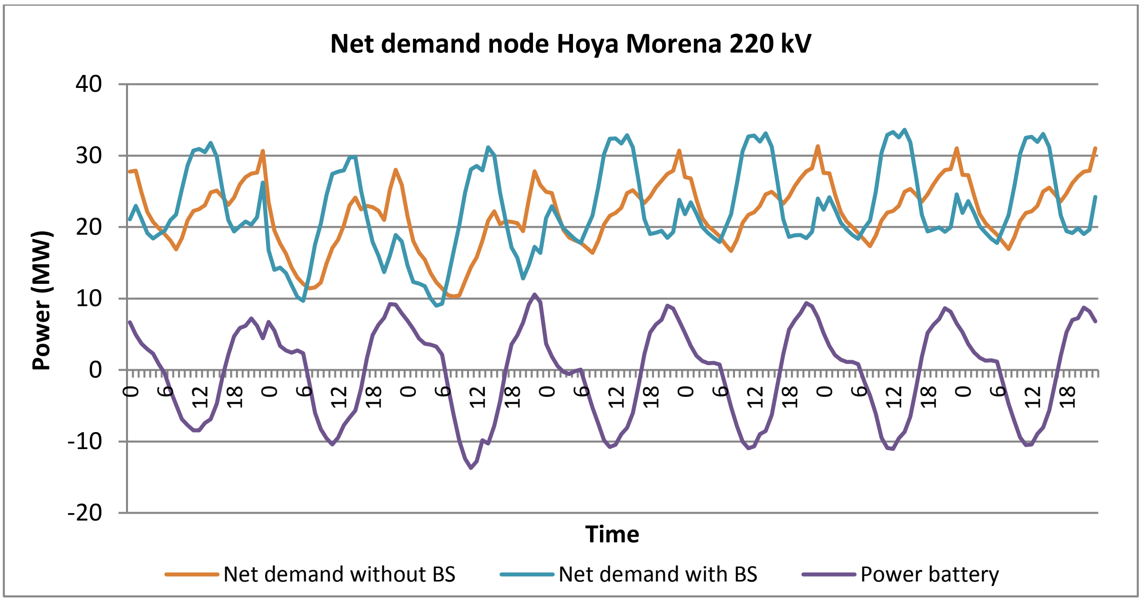


Figure 23. Net demand in the transmission busbar Hoya Morena 220 kV (from 1st August to 7th August 2025)

Finally, Figure 24 shows the operation of the battery located in Hoya Morena 220 kV over two consecutive days. As in the case of distribution, the need to maintain a certain level of charge in the battery to cope with transmission loss of load events, limits the power that can be delivered at any time by the battery.

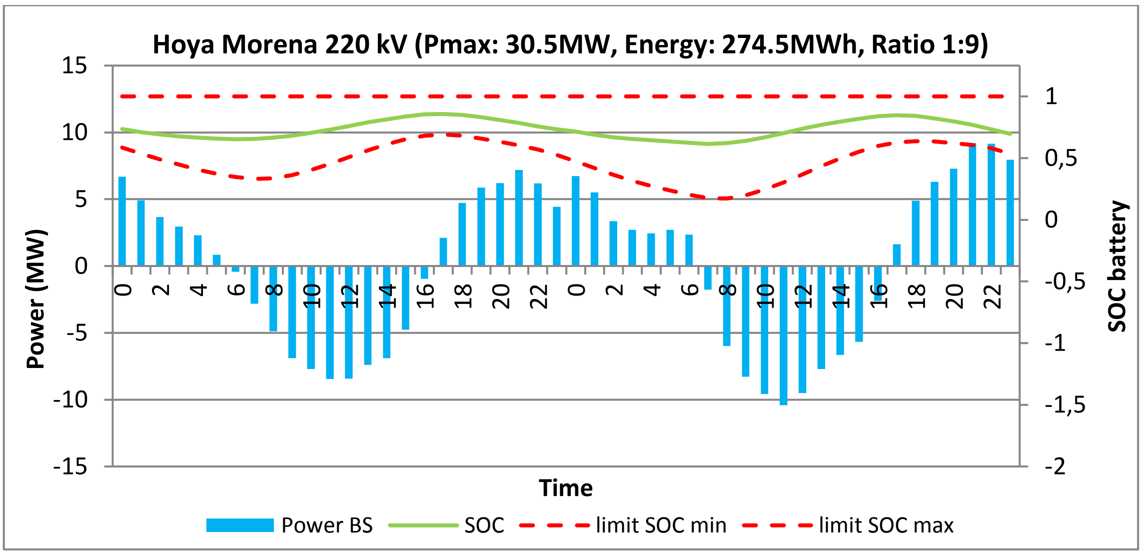


Figure 24. Power and state of charge in the battery located in the transmission node Hoya Morena 220 kV (from 1st August to 2nd August 2025)

6.3.1 Impact of batteries on voltages

The presence of batteries in the network can influence the voltage profile. To analyze the influence on voltages, the simulation has been carried out over a full year, considering the batteries installed in the medium voltage distribution network or in the transmission network. Two different assumptions regarding the control of the batteries have been considered, consisting in the operation of batteries without voltage control, injecting or absorbing only active power, and in the operation of batteries with voltage control in the node in which they are connected in the nominal value, working with a power factor between ± 0.9.

The hourly values of the voltages obtained were compared against the voltages obtained in the situation without batteries, considering both assumptions of battery control and each location alternative. Given the high number of nodes in the network, the comparison has been limited to the network areas with the greatest installed power in batteries for the case of batteries installed in the distribution network, and the areas near the area of influence of the batteries located at transmission nodes for the case of batteries installed in the transmission network.

Figures 25 and 26 show the range of variation of the distribution of voltage values obtained in each case. Specifically, the value of percentiles 5, 50 and 95 of hourly voltages is represented, compared to the limits of voltage variation allowed in the distribution network of ± 7%. It is observed that the installation of batteries in a distributed way has a positive effect on voltage, as it allows raising the lowest value of the voltage obtained with respect to the situation without batteries.

The voltage improvement is only 0.2% for the case of operation of the batteries installed in the distribution network without voltage control (Figure 25), but it reaches a value of 2.2% if the batteries are operated with voltage control (Figure 26). On the contrary, in the case of batteries installed in transmission network nodes, no difference is observed in the variation range of the hourly voltage distribution obtained, since the influence of the batteries on voltage is limited to a reduced area of the network, in comparison with the situation of deploying the same storage capacity in a distributed way throughout the network.

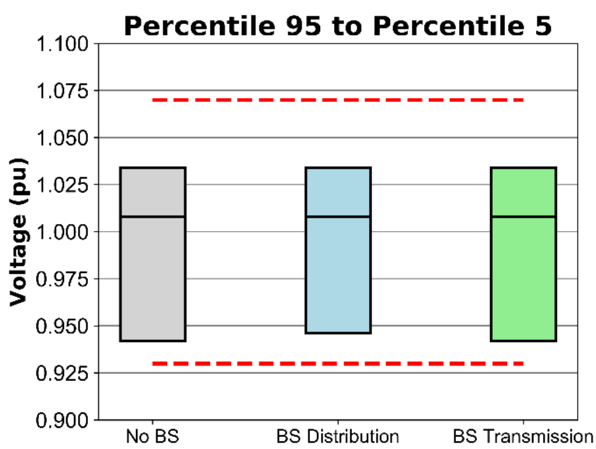


Figure 25. Effect of batteries on network voltages. Operation of batteries without voltage control

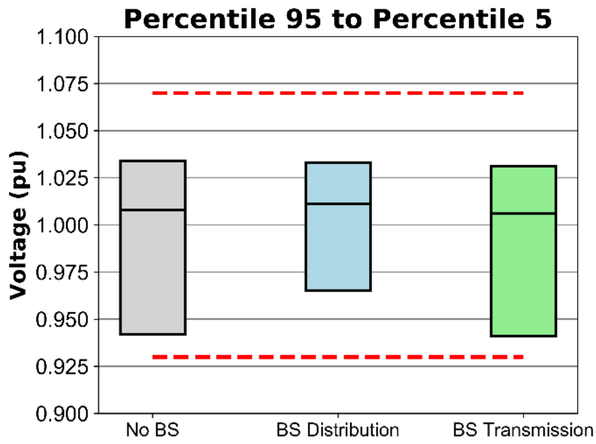


Figure 26. Effect of batteries on network voltages. Operation of batteries with voltage control

6.3.2 Impact of batteries on network losses

Finally, the simulation of the operation of batteries has allowed the identification of the influence of batteries on the value of network losses, although this influence is generally reduced because of the limited installed power of batteries in comparison with the demand on the network. Figure 27 shows the variation of annual losses in the whole network, by deploying batteries in the transmission network or in the distribution network. A reduction in losses is observed in both cases because the operation of batteries reduces the variance of the load curve and with it the power flow and losses. The reduction is greater when batteries are located in distribution, as storage is operated to optimize the load curve of the HV/MV transformers that supply the circuits where the batteries are placed, while in the case of transmission the load curve is optimized for the whole of Murcia.

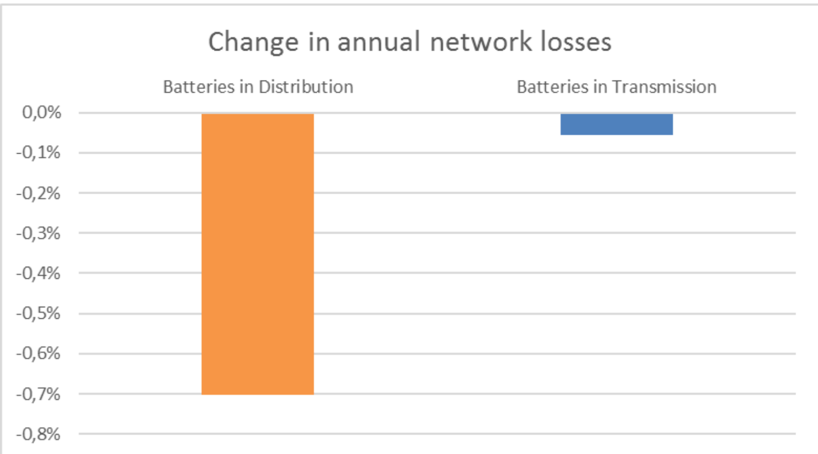


Figure 27. Change in annual network losses with batteries

However, when considering the energy losses originated in the batteries themselves and associated with the efficiency of the battery's charging and discharging, an increase of the total annual losses is observed, as losses in the batteries are higher than the loss reduction in the electricity network, as shown in Figure 28. The increase in total losses in the case of locating the batteries in transmission is greater than in the case of placing them in distribution.

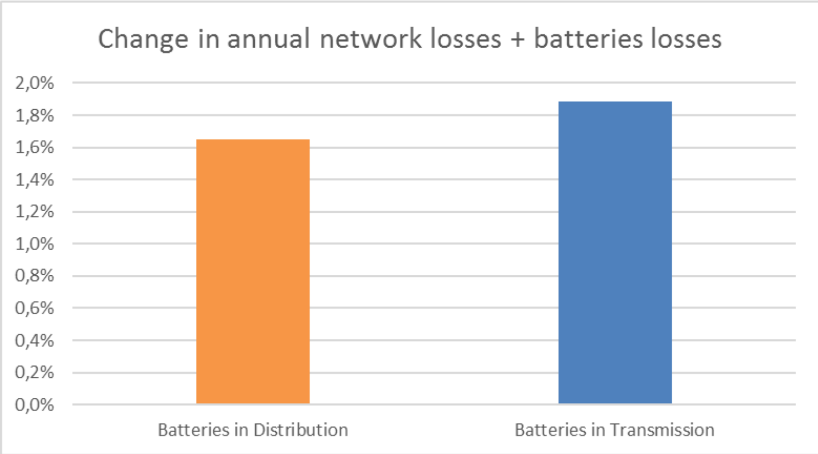


Figure 28. Change in annual total losses with batteries

To compare both cases Figure 29 shows the ratio between the variation of losses in the network and the variation of total losses (network + batteries) for each case of location. A ratio of 100% means that the increase in battery losses is offset by the reduction of losses in the network. A value greater than 100% means an improvement in efficiency, since network losses are reduced by a value greater than the increase in losses caused by the non-ideal efficiency of the batteries. On the contrary, values lower than 100% mean a loss of efficiency.

As shown in Figure 29, although there is a loss of efficiency in both cases because there is an increase in total losses, the installation of batteries in the medium voltage distribution network has a greater potential for losses reduction, as it has a higher ratio than when batteries are located in the transmission network.

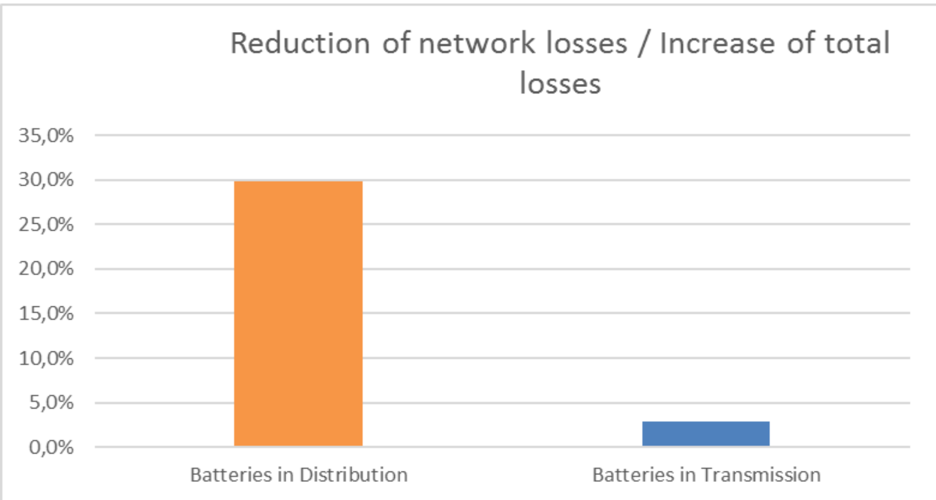


Figure 29. Ratio between savings in energy and losses of energy with batteries

In order to achieve a zero effect on total losses, batteries should improve their efficiency in the charge/discharge cycle from the 88% considered in this study to 96.4%.

In the case of the operation of batteries with voltage control, a greater variation of network losses can be observed compared to the situation without batteries (Figure 30). The location of batteries in distribution and the higher voltages derived from the operation of batteries with voltage control results in lower circulation currents for the same power demand, which produces a greater reduction of network losses compared to the operation of batteries without voltage control. However, when locating batteries in the transmission network the network losses increase slightly.

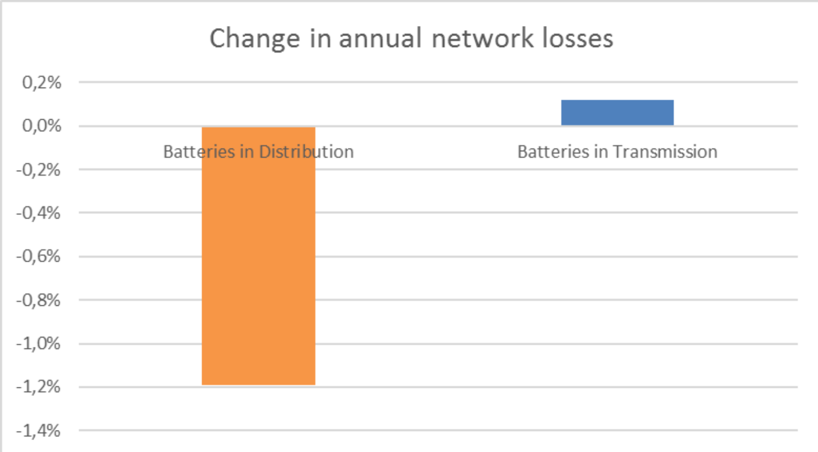


Figure 30. Change in annual network losses with batteries operated with voltage control

The consideration of losses in the batteries offsets the reduction of losses achieved in the case of batteries in distribution, producing the net effect of increasing total losses. However, the increase in losses is lower as the reduction of losses in the network is greater when operating batteries with voltage control (Figure 31). In the case of transmission, the consideration of losses in the batteries increases the value of the losses.

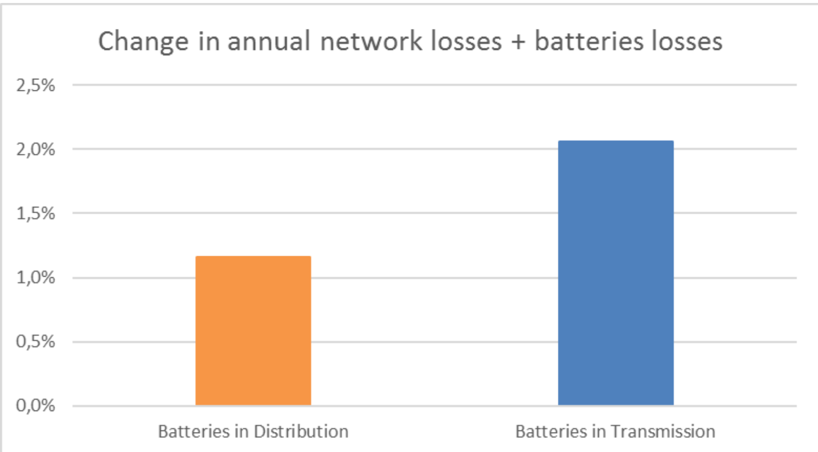


Figure 31. Change in annual total losses with batteries operated with voltage control

Finally, the increase in the value of the rate of variation of losses in the network relative to the variation of the total losses (Figure 32) shows again the greater efficiency of the installation of batteries in the distribution network compared to the transmission network, in terms of reducing losses.

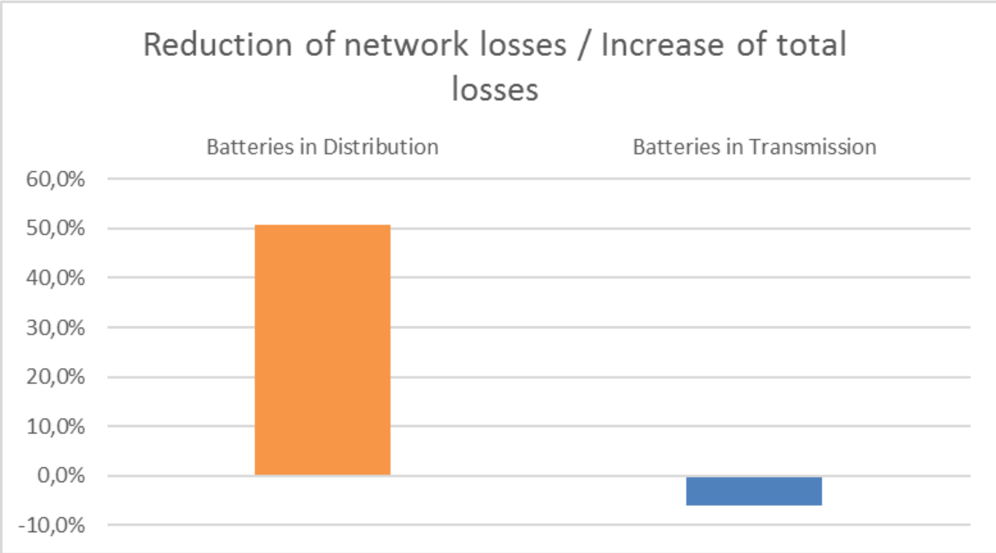


Figure 32. Ratio between savings in energy and losses of energy with batteries operated with voltage control

In this case, in order to achieve a zero effect on total losses, batteries should improve their efficiency in a charge and discharge cycle up to 93.9%.

7 Conclusions

This study has compared the location of battery storage in the transmission network and in the medium voltage distribution network. The main objective of storage is to minimize the energy not supplied in case of faults in the network. The study has proposed a similar investment budget for both scenarios, so that the results in both locations can be compared.

From the analysis, the following conclusions can be highlighted:

- Batteries located in the distribution network provide a better solution to reduce the energy not supplied in case of faults in the network, than their location in the transmission network.
- The location of batteries in the distribution network provides support for loss of load events both in the distribution network and in the transmission network, while the batteries located in the transmission network do not provide support for loss of load events in the distribution network.
- The location of batteries in distribution provides a reduction of energy not supplied that is approximately 2 times greater than if they had been located in transmission. This result has been obtained assuming a deterministic analysis, that is, the probability of experiencing a failure in the transmission network and in the distribution network is the same. In reality, this ratio will be higher, since the probability of a failure in the transmission network with loss of load is much lower than in the distribution network.
- The dispatch of batteries to reduce peak demand and improve the integration of renewable generation causes a reduction in losses in the network, being greater when they are located in the distribution network than when they are located in the

transmission network. However, when the charge and discharge performance of the batteries is taken into account, the total losses increase in both cases.

- An improvement in the performance of the cycle of charging and discharging the batteries can cause total losses not to increase. In order to achieve a zero effect, batteries located in distribution need to improve their efficiency to a lesser degree than if they are located in the transmission network.
- The location of batteries in the distribution network achieves a better network voltage profile, by increasing the minimum voltages and reducing the range of variation. This effect is improved when batteries are operated with voltage control.

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Annex I

The calculation of Energy Not Supplied (ENS) due to a contingency that is shown in this study has been determined using a deterministic method, that is, assuming that the probability of occurrence for each failure is equal to 1. However, for a more accurate calculation of reduction in ENS produced by the use of batteries, it is necessary to take into account the failure rate of the different network elements, that is, to perform the calculation following a probabilistic method. This annex presents the results of the reduction in ENS calculated following a probabilistic method and compares them with the results of the deterministic method.

The first step is to know the failure rate associated with each contingency. Iberdrola has provided this data, classified according to the origin of the contingency:

1. MV overhead line: 5.95 failures/100km/year
2. MV underground cable: 5.08 failures/100km/year
3. Underground secondary substation transformer: 6.58 failures/100ST/year
4. Aboveground secondary substation transformer: 2.53 failures/100ST/year
5. HV overhead line: 0.24 failures/100km/year

Taking into account the length of MV lines of each type (overhead and underground), number of secondary substation transformers of each type (underground and aboveground) and the length of the transmission lines for the network in Murcia, the following failure rates have been obtained by type of network element:

1. MV overhead line: 1.03 failures/year
2. MV underground cable: 0.88 failures/year
3. Underground secondary substation transformer: 0.0658 failures/year
4. Aboveground secondary substation transformer: 0.0253 failures/year
5. HV overhead line: 2.02 failures/year

To calculate the ENS associated with each contingency, the same duration as used in the deterministic calculation has been considered: 3 hours for overhead MV lines and aboveground SST, 9 hours for underground MV cables and underground SST and 9 hours for HV overhead lines.

Table 4 shows the results of the calculation of ENS according to the probabilistic method along with the results of the deterministic method, for the scenario without batteries, and for the scenarios with batteries located in the distribution network and in the transmission network. This same comparison is shown in Figure 33 for the 2025 winter peak and in Figure 34 for the 2025 summer peak.

As can be seen, the consideration of the probabilistic calculation reinforces the conclusions of the study in that the effectiveness of the batteries to provide network support during contingencies is much greater if they are located in the distribution network than if they are located in the transmission network.

	Winter Peak 2025			Summer Peak 2025		
	DNS (MW)	ENS Det (MWh)	ENS Prob (MWh)	DNS (MW)	ENS Det (MWh)	ENS Prob (MWh)
No Batteries	406.6	3554.6	2871.6	330.4	2869.4	2353.3
Batteries in Distribution	295.2	2582.1	2040.4	270.2	2346.5	1926.1
Batteries in Transmission	355.0	3090.2	2847.4	286.0	2469.8	2332.5

Table 4. Comparison of ENS calculation with deterministic and probabilistic methods

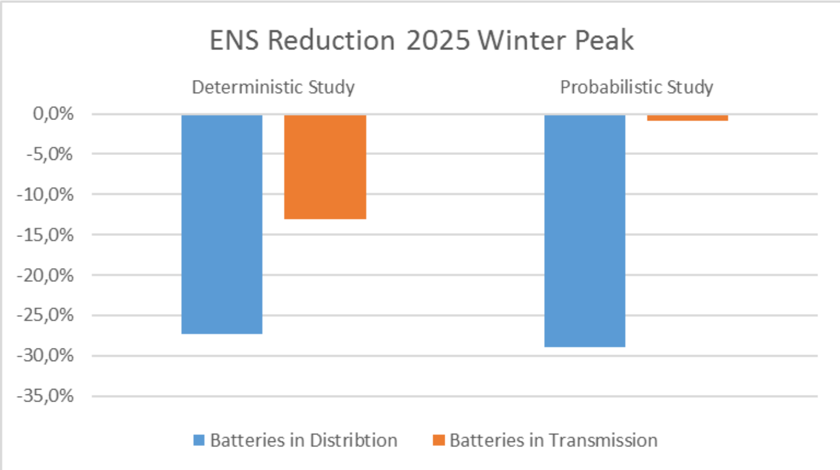

Figure 33. ENS reduction for 2025 winter peak. Comparison between deterministic and probabilistic methods

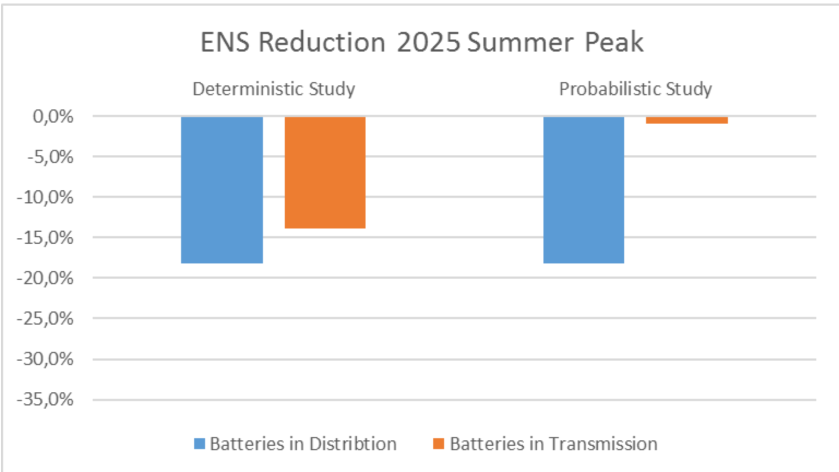

Figure 34. ENS reduction for 2025 summer peak. Comparison between deterministic and probabilistic methods