# GEDISPER Project

# Final Report


Prepared by:

Pablo Eguia, Esther Torres y Javier García


28 July 2016, Bilbao

Version: 0


Escuela Técnica Superior de Ingeniería de Bilbao (UPV/EHU). Dpto. Ingeniería Eléctrica
Alda. Urquijo s/n, 48013 Bilbao

# Executive Summary

GEDISPER is a research project that aims to **discover the actual distributed generation impacts on network losses** linked to PV self-consumers connected to low and medium voltage in energy losses. A detailed analysis has been carried out using real models of transmission and distribution networks and actual power demand data throughout a year. In particular, this study has been **focused on three Spanish regions**, **Murcia**, **Madrid** and **Biscay**, during the year 2014.

The project considers several PV self-consumption development scenarios. The size of solar panels to be installed (the percentage of consumer's demand) is deemed to be conditioned by the regulatory framework adopted. Also, this study analyzes scenarios of self-consumption development with different geographic distributions; from a very evenly developed to a more concentrated one. At the same time, different penetrations of consumer adoption of self-consumption have been studied, from no adoption to maximum consumer adoption (i.e. all consumers become prosumers).

For each possible combination, power flows in the network have been calculated, calculating the losses for the whole electricity grid.

The study shows that self-consumption policies aimed at minimizing exports to the grid (referenced in the study as **Instantaneous consumption**), yield a general reduction in losses both in transmission and distribution networks, for all adoption levels and all geographic concentration scenarios considered.

In contrast, for regulatory frameworks with a higher compensation for excess power sent to the grid (**referenced in the study as deferred consumption**) the results show that losses get reduced when the adoption level is low or moderated but increase when the adoption level is higher. Furthermore, in these cases the geographic concentration becomes significant.

Moreover, from a global energy efficiency point of view, the study shows that replacing centralized generation with distributed generation is efficient at low penetration levels due to a higher sensitivity to loss reduction. However, as the penetration of distributed generation increases, the lower sensitivity to loss reduction produces a very low or even negative efficiency gain when centralized generation is replaced with distributed generation. The efficiency gain due to generate solar PV on a distributed fashion compared to large scale centralized power stations is always below 10%

The study also analyzes the overvoltage problems that appear as a consequence of high self-consumption levels. The conclusions are that in scenarios that minimize the surplus sold back to the grid the effects on Low Voltage grids are not significant. On the other hand, under a deferred consumption framework (installations that are sized to produce 100% of the yearly consumption), **overvoltage problems are observed in MV and LV**, with increasing relevance as self-consumption adoption grows. The analysis allows us to conclude that using smart inverters (able to control voltage managing reactive power) is effective in keeping voltages within statutory limits but would induce higher losses.

The study conclusion is that Distributed Generation coming from Photovoltaic self-consumption does not always reduce losses. In certain cases losses can even increase with respect to initial levels.

# 1 Introduction

## 1.1 Project purpose

The electric system as it is known for most of the last century, has been conceived as a system where bulk generation plants, far from consumption centers, delivered power to high voltage transmission lines, that then transmitted it gradually to lower voltage lines up to the client. This process of generation, transmission and distribution results inevitably in losses due to power currents flowing through the Networks connected cables.

Thanks to cost reductions and modularity, solar photovoltaic power scalability is called to play an important role in the future grid. Solar PV will be developed both at utility scale and as distributed generation linked to self-consumption or not.

The rapid fall in prices and the great modularity, the solar photovoltaic (PV) power play an important role in the future grid. Solar PV can be developed as utility scale or distributed energy resources (DER) linked to self-consumption or not.

Usually the reduction of networks losses is referred as one of the benefits of distributed generation, in those cases where distributed generation is located at or near the point of end use, avoiding transport from long distances and to be transformed several times to different voltage levels, in this case, it could be assumed that the distributed generation losses are reduced than the bulk generation system, where the energy is produced far away from consumption centers.

This argument is commonly used to justify promoting distributed generation as well self-consumption.

However, the solar PV power is intermittent and depends on meteorology, and therefore the generated power does not follow the demand power curve of the prosumer each moment. In other hand, this fact changes the condition of the Network as a supply chain for electric power as we known including bidirectional flows and the distributed PV generation will tend to use the power grids more than one might initially think when there is not enough consumption close to the generation point. It is therefore questionable whether the distributed generation.

Following this argument, The electrical department of Basque Country University (Spain) by initiative of *Energía y Sociedad*, carry out a research project with intention to analyze the actual impacts on network losses due to different levels of PV distributed generation in MV and LV network. A detailed analysis has been performed, using actual data of the distribution and transmission grids and actual power demand values for a whole year. The aim was to find out under what circumstances distributed generation effectively reduces grid losses.

The project has proposed several scenarios of self-consumption development as main driver of distributed generation in Medium Voltage (MV) and Low voltage (LV) networks. In this context, different regulatory frameworks are developed in order to regulate the deployment of this type of installations considering the adoption level and geographic concentration: from a very homogenous to more disperse scenario.

For each scenario, is calculated the power flows throw the electrical grids at every hour through the day have been calculated; from night time when solar PV generation is null to summer day when solar PV generation is maximum.

## 1.2 Distribution grid losses

Energy losses in electrical systems are an avoidable1 consequence caused by the electrical flows from generation plants until the point of end consumption.

These losses, even when depending on technical characteristics of the system and its demand (see table 1), in real electrical systems are around 9% of total generated power. The losses impact to all network system, especially on MV and LV distribution networks.

| Country | 1980 | 1990 | 2000 | 2004 |
|---|---|---|---|---|
| Finland | 6,2 | 4,8 | 3,7 | 3,6 |
| Netherlands | 4,7 | 4,2 | 4,2 | 4,2 |
| Belgium | 6,5 | 3,0 | 4,8 | 5,0 |
| Germany | 5,3 | 5,2 | 5,1 | 6,7 |
| Italy | 10,4 | 7,5 | 7,0 | 7,1 |
| Denmark | 9,3 | 8,8 | 7,1 | 5,4 |
| United States | 10,5 | 10,5 | 7,1 | 7,3 |
| Switzerland | 9,1 | 7,0 | 7,4 | 7,1 |
| France | 6,9 | 9,0 | 7,8 | 7,7 |
| Austria | 7,9 | 6,9 | 7,8 | 5,2 |
| Sweden | 9,8 | 7,6 | 9,1 | 8,4 |
| Australia | 11,6 | 8,4 | 9,1 | 7,4 |
| United Kingdon | 9,2 | 8,9 | 9,4 | 9,4 |
| Portugal | 13,3 | 9,8 | 9,4 | 9,1 |
| Norway | 9,5 | 7,1 | 9,8 | 8,1 |
| Ireland | 12,8 | 10,9 | 9,9 | 8,9 |
| Canada | 10,6 | 8,2 | 9,9 | 7,8 |
| Spain | 11,1 | 11,1 | 10,6 | 8,7 |
| New Zealand | 14,4 | 13,3 | 11,5 | 15,6 |

*Table 1: Energy Losses, percentage of the generated power for different electrical systems [1]*

Electricity LOSSES are classified according to their origin [2]:

1. Technical losses (kWh): losses related to the technical characteristics of facilities for power supply. Those losses have their origin on the current flow through the network equipment and because the network equipment are under voltage. In this sense, the technical losses are classified according to their physical origin:

   - Load losses: are produced by the current flow through the network equipment (Joule effect), transformers losses, etc…

   - No-load losses: occur to maintain voltage network equipment energized. Caused by the corona effect, hysteresis and eddy currents. As reference, in a regular distribution network the no-load losses represents between 1/3 and 1/4 of the total technical losses in the network.

2. Non-technical losses (kWh): electricity supplied and consumed but not accounted. Strictly speaking, these losses represent the difference between total network losses and technical losses, they are classified as:

   - Administrative losses: are directly attributable to deficiencies in the administrative management of utilities (measuring errors, invoicing errors, etc.).

- Theft: final users who misappropriation energy through illegal connections or unregistered temporary facilities.
- Fraud: losses associated with falsified electrical meters which recording less consumption than actual power consumed

In this study only taken into account the technical losses as distributed generation photovoltaic affects these losses by changing power flows of network elements.

## 1.3 Previous studies tackle the question of losses on networks

There are several studies related to electrical networks losses owing to penetration of PV distributed generation. Next, we analyzed the most relevant studies highlighting its findings.

### 1.3.1 MIT, *The Future of Solar Energy.* An Interdisciplinary MIT Study. 2015

The MIT study [3] examines the PV deployment impact in USA, taking into account several technologies; identifying which regulatory frameworks changes that might be more effective to support the growth of long term distributed generation (DG).

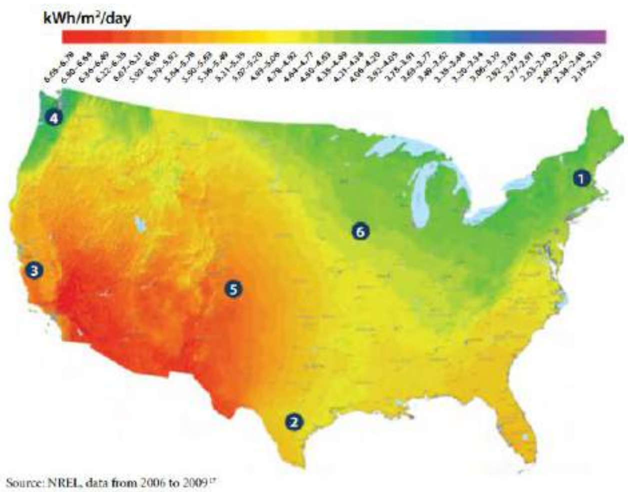
This study is mainly based on three characteristics of distributed photovoltaic generators: (1) generators are geographically random located; (2) generation is variable due to the solar cycle and cloudy days; (3) generation is uncertain because it follows an irregular pattern. The study analysis on how energy losses are affected by different design of rates approaches.

**Metodology**

MIT designs several prototypes networks with different characteristics (simulations), they studied several scenarios in which different amounts of PV generation have been added at an unspecified point in the future, using a Network Reference Model (NRM) that calculates the optimal distribution network:

- *Greenfield* mode planning produces a detailed design of the least-cost network in a scenario that lacks any constraints imposed by prior infrastructure investments.
- Network RNM is used to calculate additional network cost and losses.

The host networks in our analysis are based on regions with high and low population densities in six diverse parts of the United States. For each of the six states, MIT chose two specific locations — one with low population density and the other with higher density [kW/km2], as is showed in the figure 1.




| Number | State | Low Density | High Density |
|---|---|---|---|
| 1 | Connecticut | Torrington | Hartford |
| 2 | Texas | San Marcos | Austin |
| 3 | California | Lancaster | Los Angeles |
| 4 | Washington | Covington | Seattle |
| 5 | Colorado | Eaton | Boulder |
| 6 | Iowa | Altoona | Des Moines |

*Figure 1: Locations and densities of the MIT study*

For location and density of the DG (Distributed Generation), street maps are used, the DG is located according to a probability distribution from random draw until a uniform probability distribution.

**Simulations**

For each network, are analyzed 8 stages with different photovoltaic penetration, the total capacity assumed for each scenario is such that yearly PV electricity output ranges between 0% and 40% of yearly load.

How to locate the loads is based on reality, analyzing the size and type of each generator. Values for expected demand growth, ranging from 0% to 30%, and is considered 3 types of generation: residential, commercial and industrial.

**Results and conclusions**

In terms of costs, the Network will be reinforced to absorb the fluctuations produce by the balance between generation and load. In the case of generators connected to the distribution network, bidirectional protection, filters, implementation of security measures, etc.

The penetration of the solar DG on distribution network first can reduce the network losses. However, when the penetration of PV reaches higher levels, the distribution costs are increased, caused by the necessary new investments of the bi-directional flows to maintain the same quality of service.

The electrical losses are lower in places with greater capacity factor because the network is able to absorb the peak generation, whereas in locations with low irradiation is required further installed capacity to achieve the same demand, so the stresses generated are bigger during irradiation peak generation. MIT finds that rural networks tend to require significant upgrades in the HV network, while urban networks usually require larger investments in LV equipment

Energy storage can be seen as an alternative to investing in conventional network equipment to accommodate high PV-penetration scenarios, in some cases. Also, it is important to analyze the most appropriate size of the batteries and their optimal location

In conclusion, the MIT highlights the importance of establishing a policy of pricing CO2 emissions as the most efficient solution with lower costs, since the volumetric rates and net metering do not contribute to efficient management system.

### 1.3.2 IIT (IEEE paper), Assessment of Energy Distribution Losses for Increasing Penetration of Distributed Generation. 2006

IIT study [4] analyzed the impact of losses caused by several technologies of Distributed Generation (GD), according to DG penetration and concentration levels. Based on a more decentralized future, which small generation units are connected directly to the distribution network close to demand points.

**Network Model and Algorithm**

The study calculates the losses taking into account the load demand and DG production for every hour of the year. To analyze the overall impact of DG on losses, several scenarios with different DG technologies, penetration, and concentration levels were created, for different radial networks of Medium Voltage (MV), according to "IEEE 34-node test feeder" model, shown in Figure 2.

Where, DG penetration is defined by the following formula:

$$\textbf{DG penetration} = \frac{\text{Capacity Factor x DG Installed Capacity}}{\text{Feeder Capacity}}$$

And the simplified network diagram "IEEE 34 node test feeder" is:

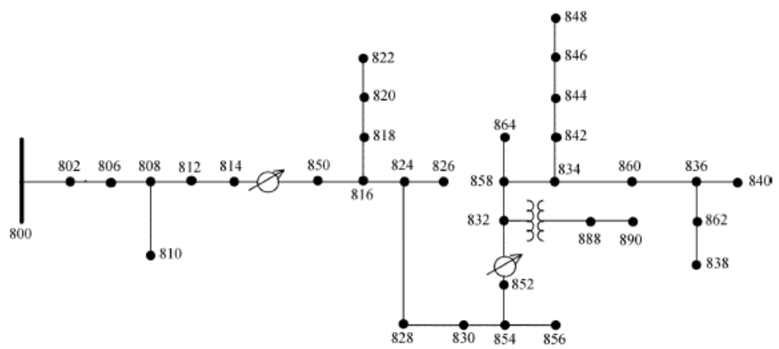



*Figure 2: Line Diagram IEEE 34 node test feeder*

DG units are characterized according to their constructive technology (CHP, wind farms, photovoltaic, micro turbines, etc.), and their reactive power control scheme, with several load scenarios

Similarity to our study, we will highlight the photovoltaic technology, for which has been simulated hourly radiation applying correction factors to include the effect of cloudy days and radiation by location.

The computation of energy losses on an hourly basis requires the knowledge of hourly energy consumptions in each load node. The selected IEEE 34-node test feeder does not provide hourly load data. For this reason, the IEEE load data have been assumed as peak demands and demands for the rest of the year were obtained, assuming the same load evolution as real historical hourly data from Spanish consumers.

Regarding DG concentration levels, the following scenarios were created:

- "Ideal" scenario, The DG installed capacity in each node was proportional to the load demand in that node.

- "3 GD" scenario, three same-size DG plants were located strategically along the feeder to obtain a well-balanced load situation

- "1 GD" scenario, one single DG plant was located alternatively in different nodes along the feeder.

The DG penetration level was gradually increased from 0% (base case) to 15%.

A load flow algorithm should be run each hour of the year called “The Newton–Raphson (N–R)”. Radial load flow is used for large networks.

**Results and Conclusions**

The Figure 3 shows the results of the study. In the "ideal" scenario, the evolution of losses for different DG shows that losses start to decrease when connecting small amounts of DG until they reach their minimum level. Once this minimum level is reached, if DG penetration level still increases, then losses begin to marginally increase too. If DG penetration levels increase enough, then losses can be even higher than without DG connected (more than 5 times in extreme cases). This type of shape has appeared in all studied cases.

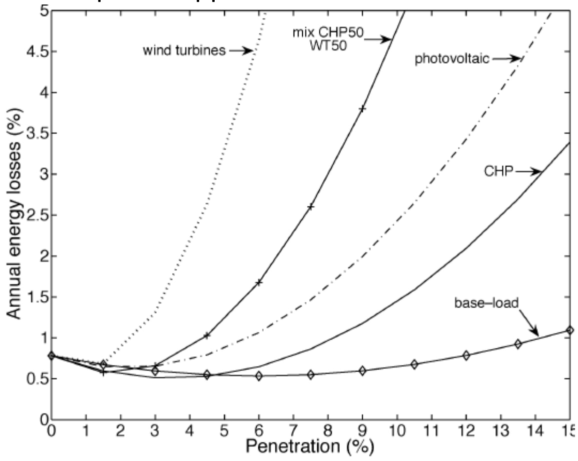



*Figure 3. Annual energy losses, IIT study*

"3 GD" scenario the DG is located in 3 well identified nodes, the results are quite similar to the "ideal scenario".

"1GD" scenario with a DG plan connected in a specific node the losses are higher than in the above-mentioned cases

This study takes into account the capacity factor of each technology, while for Spain the maximum of 50% for each feeder (a total capacity of 713 kVA is assumed); corresponding to a penetration rate of 6.25% for photovoltaics.

For instance, in Spain, the maximum DG installed capacity in a distribution feeder should be kept lower than 50% of the maximum feeder capacity (maximum feeder capacity of 713 kVA), which would correspond with a penetration level of 6.25% of FV plants.

Other analysis of this study is comparison of energy losses variations under two different reactive power control situations, distributions system operator (PV model) and PQ node. The maximum reactive power that DG can supply or consume was set at a power factor equal to 0.8. In conclusion, supply reactive power during peak hours or to consume it during off peak hours has a beneficial effect on voltages and losses. Furthermore, an appropriate design of voltage control can have positive effects on the annual losses.

### 1.3.3 Imperial college, Grid Integration Cost of Photovoltaic Power Generation. 2013

This study [5] analyze and quantify the costs and benefits of the DG penetration to the network on 11 European countries, with aim of reaching 12% of electricity demand in EU by 2020, the following aspects are analyzed:

- The costs of backup capacity (as batteries) can become a significant cost in the DG penetration, especially in northern Europe, around 14.5 € / MWh
- Distribution networks reinforcements are need to integrate PV generation, could be around 9 € / MWh in 2030, the costs are necessary to absorb misalignments between generation and demand.
- Transport costs are also an important cost, estimated at 0.5 € / MW in 2020 and 2.8 € / MW in 2030
- Another component, is the balance costs in the European market will 1 € / MWh in 2030
- Electrical losses in distribution networks that are low penetration levels (10%) losses are reduced but the trend was reversed over 10% penetration.

In conclusion the cost of PV penetration between 2% and 18% is modest, it is estimated to increase around 26 €/MWh by 2030. In addition, the report shows that applications "Demand Response "or storage solutions can reduce the negative effects of PV integration up to 20%.

## 1.4 Royal decree of self-consumption in Spain

Royal Decree (RD) 900/2015 [6], enacted on 9th October 2015, regulates the administrative, technical and economical arrangements of supply and production of electrical energy self-consumption, defined in the law 24/2013, of 26th December, as power consumption from generation plants connected within a network of a consumer or through a direct line of energy associated with a consumer, also the Royal Decree distinguishes several varieties of self-consumption.

RD states that the power generation activity has been characterized as centralized power generation, with unidirectional electrical flows and with incentive measures and control over the demand management. The new power consumption modalities move forward a distributed generation model, generally small power, and normally with bi-directional flows

RD shows that Distributed generation is beneficial for the electricity system, especially in relation to loss reduction, in those cases where distributed generation is close to load centers, assuming further minimizing the impact of electrical installations in their environment.

RD continues alleged that distributed generation does not reduce the maintenance costs of transmission and distribution networks or other costs of the electrical system, in some cases, additional investment costs in networks to absorb the new necessities produced by the distributed generation.

Also, RD aims a distributed generation system with a promote mechanism of surplus selling and Instantaneous self-consumption to boost individual energy production in small power plants for self-consumption at the same place of production.

### 1.4.1 Technical and administrative conditions of Royal Decree for self-consumption

The self-consumption modalities according Royal Decree are:

Self-consumption Type 1, generation with self-consumption, only to self-consumption

- Contracted power shall not exceed 100 kW, and the total installed power generation will be equal or less than the contracted power by the consumer.
- The excess energy can be delivered to the network while no financial compensation is receiving.
- A single entity, the consumer
- Measuring equipment:
  - Metering device records the net energy generated by the power generation facility
  - Metering device is independent measured at the connection point of the installation
  - Optionally, a meter which records the total consumed power by the prosumer.

Self-consumption Type 2, generation with self-consumption, the prosumer with self-consumption and sell the surplus power

- The total installed power of the generation facilities will be equal or less than the contracted power by the consumer
- Prosumer can supply the surplus power to network and recieve a economical compensation.
- Two entities, consumer and producer, called prosumer

- Measuring equipment:
    - The metering device is bi-directional to measure the net energy generated
    - The metering device records the total energy consumed by the consumer associated
    - Optionally, bi-directional metering device located on the border of the installation point.

There are several considerations that affect both self-consumption methods, these are:

- Under no circumstances, a generator can connect an inside wing network of several consumers
- All prosumers must apply for administrative register of self-consumption of electrical power
  The off-grid systems and the backup diesel generator used exclusively in case of an interruption power from network connection are excluded of the application of this Royal Decree.

- Batteries can be used under this RD in case those have the necessary protections under the applicable industrial normative of security and quality shall be installed to keep sharing the meter which registered the net generation or the measuring device recorded hourly consumed power.

- The access contract will be done with the distribution company directly or with the retailing company. Other option is modify the existing contract according to the applicable normative.

### 1.4.2 Economic conditions of the Royal Decree

With intention to ensure the technical and economic sustainability of the bulk system, self-consumption installations connected to such electrical system should contribute to the financing of costs and system services in the same way as other consumers. Conversely, an off-grid system no assumes any cost of the electrical system.

The self-consumption facility connected to network, which provides consumers with a number of natural benefits, so, should contribute financing the costs of the bulk system as other consumer’s do, reason to apply tolls access to transmission and distribution networks, loads related to system costs and loads for other system services.

Access tolls to transmission and distribution networks as a contribution to cover the costs of such networks will be paid for actual use made of them.

The loads associated with the electricity system costs are primarily intended to cover (1) the specific remuneration system for renewable generation, (2) high-efficiency cogeneration and waste, (3) the over cost of generation in non-mainland territories, and (4) the annual payments for the deficit of electrical system.

Temporarily, until the loads associated with the system costs are approved, the loads taken into account are for other system services that try to compensate both the support required by the system to ensure the balance between generation and demand on the daily period and in real time as the necessary capacity for that balance in the medium and long term. So shall apply to self-consumption few fixed loads based on the power (€/kW) and a term variable load to be applied to the self-consumed energy during the transitional period (€/kWh), although Royal Decree considers certain exceptions, as they are:

- Small consumers, consumption mode type 1 connected to low voltage and less than or equal to 10 kW contracted power.

- Off-grid systems from non-mainland electrical systems, such as Canary Islands, Ceuta and Melilla, Ibiza-Formentera electrical system, and a reduction for the Mallorca-Menorca system.

- Cogeneration is exempted until December 31$^{st}$ 2019.

# 2 Methodology

The influence of the PV generation on network losses depends on solar irradiation, the technical characteristics and demand power of the network. Therefore, in order to provide general conclusions in this study we have analyzed three different zones:

1. Murcia
2. Madrid
3. Bizcay

There are several concerns about the massive deployment of PV self-consumption installation about reduce or increase the energy losses, although the photovoltaic generation connected studied in distribution networks MV and LV, the study has taken into account the high voltage network. In Figure 4 is showed the network topology analyzed, which has been divided into three voltage levels:

1. HV Network is the mainland transmission network system. Estimated electrical losses included the losses of transmission lines, generation transformers, auto-transformers and power transformers from distribution (MV) to transport (HV).
   - Madrid: HV from 45 kV
   - Bizcay: HV from 30 kV
   - Murcia: HV from 66 kV
2. MV Network includes Medium Voltage distribution network of each studied area. The calculated losses include losses in medium voltage lines and the HV / MV transformers that feed them.
   - Madrid: MV from 1 kV until 20 kV
   - Bizcay: MV from 1 kV until 13.2 kV
   - Murcia: MV from 1 kV until 20 kV
3. LV network. It comprises a representative number of low-voltage fed from the medium voltage network. Estimated losses include losses in low voltage lines and transformers processing centers that feed them.
   - Madrid: LV below 1 kV
   - Bizcay: LV below 1 kV
   - Murcia: LV below 1 kV

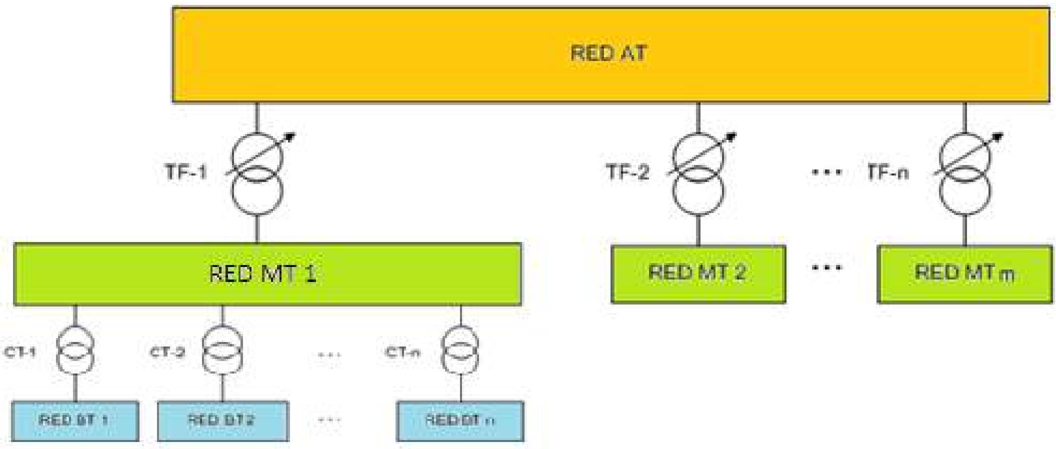



*Figure 4. Network model by voltage level*

The HV model (Figure 5) used in the study is the complete mainland transmission network system which includes connections with France, Portugal and Morocco. This model shows the operation status of transmission network for the peak demand on summer 2004. The model is completed with information of HV / MV power transformers of each network zone studied and generation plus demand are simulated for the studied days in 2014 from information published by REE [7].

*Figure 5. Network HV mainland Network HV model for the study*

The MV network model for each network area studied has been supplied by Iberdrola and sees each HV / MV transformer together with its network of MV associated, including charging customers MV, the burden of processing centers to LV and the connected distributed generation. The combination of involve elements, similar to the simulation software used; it is called area. In other words, each MV distribution network analyzed is composed for a number of areas. These areas are interconnected and powered by HV network.

The Figure 6 shows the model of the MV network for Murcia zone obtained from PSS/E software package for modeling and network design. Each color corresponds to an area of the network.

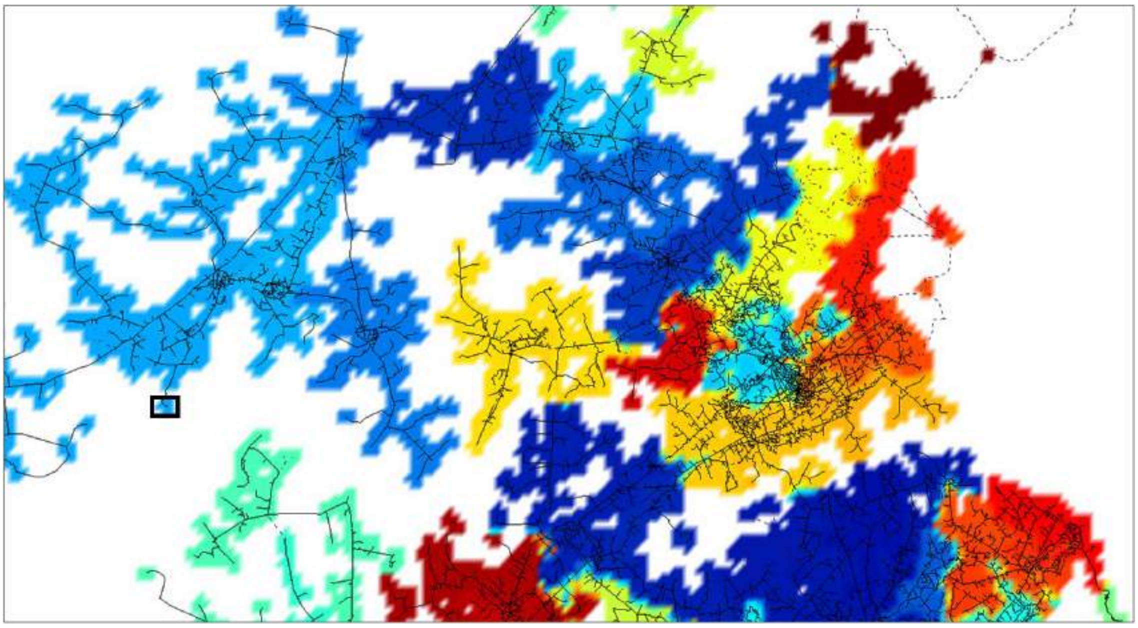


*Figure 6. MV Network Model of Murcia zone*

Finally, the LV network model, also provided by Iberdrola, has not been seen entirety due to the unavailability of data processing and the inability to model them simultaneously in PSS/E software. Thus, it has modeled a representative set of 40 LV networks for each zone studied. For this set the study has been analyzed in detail the electrical losses, from the results, losses have been estimated for the entire LV network. See the figure 7, a sample of LV network in Murcia zone, also obtained from PSS/E software.

*Figure 7. sample of LV network model of Murcia zone*

The tables 2 to 4 shows a detailing number of network elements referred to in the full model of each three distribution zones studied. The HV model is common for the 3 zones.

| | Networks | Buses | Generators | Loads | Transformers | Branches |
|---|---|---|---|---|---|---|
| HV Network | 1 | 2674 | 655 | 989 | 1243 | 3788 |
| MV Network | 90 | 31721 | hasta 15388 | 15388 | 94 | 33327 |
| LV Network | 40 | 19020 | hasta 13651 | 13651 | 71 | 18949 |

*Table 2. Network model data of Murcia*

| | Networks | Buses | Generators | Loads | Transformers | Branches |
|---|---|---|---|---|---|---|
| HV Network | 1 | 2674 | 655 | 989 | 1243 | 3788 |
| MV Network | 259 | 42871 | hasta 19064 | 19064 | 259 | 47839 |
| LV Network | 40 | 3874 | Hasta 2555 | 2555 | 87 | 3775 |

*Table 3. Network model data of Madrid*

| | Networks | Buses | Generators | Loads | Transformers | Branches |
|---|---|---|---|---|---|---|
| HV Network | 1 | 2674 | 655 | 989 | 1243 | 3788 |
| MV Network | 90 | 13715 | hasta 6543 | 6543 | 105 | 14712 |
| LV Network | 40 | 2835 | hasta 1662 | 1662 | 69 | 2762 |

*Table 4. Network model data of Bizcay*

## 2.1 Definition of FV generation scenarios

For each of the three network zones studied were created 132 different penetration scenarios of PV generation according to three dimensional designs:

1. Adoption level: the total demand porcentage of the distribution network which is covered by self-consumption (11 levels).
2. PV sizing: the percentage of demand for each customer that is covered by the installation of self-consumption (2 levels).
3. Geographic concentration: define how PV generation is geographically located within the network (6 scenarios).

Next, the criteria for each dimension is detailed described:

### 2.1.1 Dimension 1: Adoptation Level

The adoption level defines the total demand percentage of consumers within MV and LV network which is covered by self-consumption. They have seen a total of 11cases of adoption from 0% to 100% in 10% steps. Approximately, this level match the consumer's percentage within the MV and LV network who embrace the PV self-consumption.

As an example, Figure 8 shows on the map the effect of considering different adoption levels of self-consumption on MV and LV networks in Murcia region, each point representing the number of prosumers who have PV self-consumption in MV or LV. The color marks the number of customers with self-consumption per km2 being White 1 to 5; Yellow 6-10; Orange 11-15; Red 16-20; and dark more than 20.

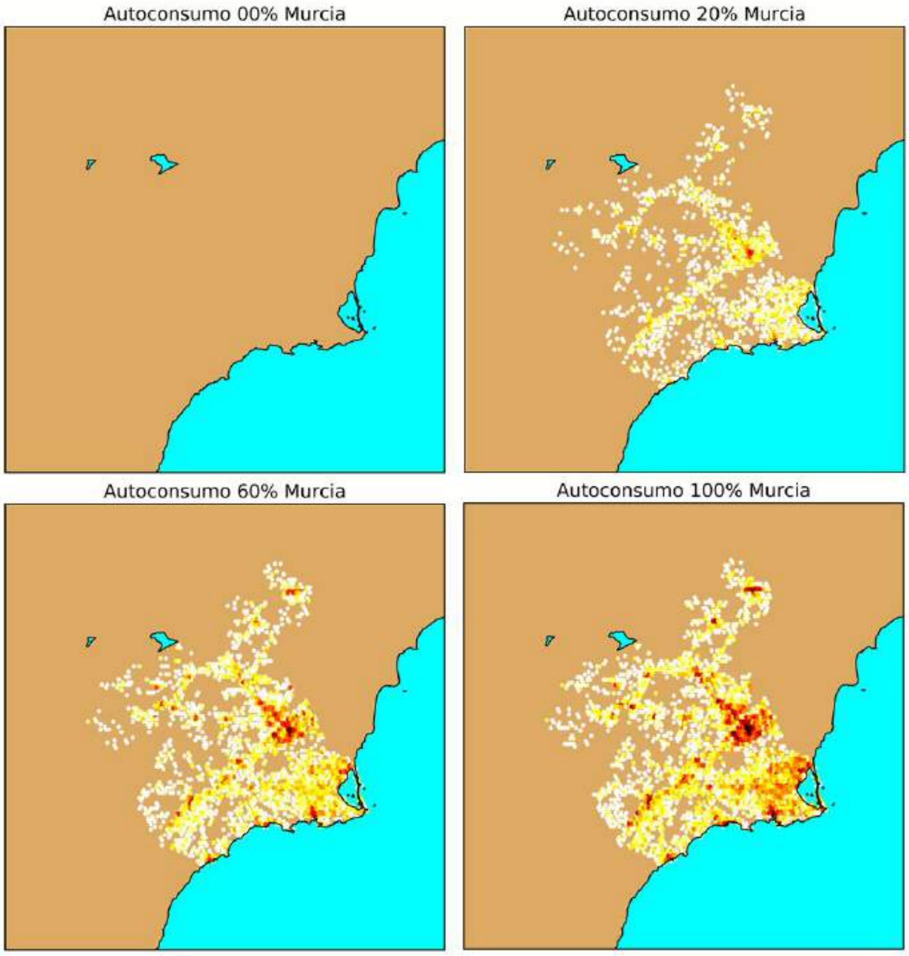



*Figure 8. Example of different adoption levels for Murcia network*

### 2.1.2 Dimension 2: PV sizing

The PV sizing defines the total power that the PV generator produces per year in connection with customer demand. While each customer is free to decide the sizing of installation, following an economic criterial, the PV sizing is determined by the taxes applicable according the regulatory framework in force. Thus, the design of the PV system is based on two possible policies of self-consumption incentives.

1. Instantaneous consumption (ISC): a regulatory framework in which energy spillage has an economic valuation according the wholesale market prices. For these reason, so the user designs an installation with a power surplus minimizing disloads to the network. Thus, the PV system is designed to provide 40% of the annual energy demand of the prosumer.

2. Deferred consumption (DC): a regulatory framework in which energy surplus generation not consumed Instantaneous has an economic valuation bigger than the wholesale market prices, close or equal to the retail price of electricity market price. Thus, the PV system is designed to provide 100% of the annual energy demand of the prosumer.

For sizing, they have adopted simplified design conditions. It was considered an optimal orientation of the panels without shadows. In addition, average values have been used for irradiation, which means that the estimation of losses and voltage of the study is conservative. That is, when the quadratic power losses, lower losses on cloudy days are not offset by higher losses on sunny days. This effect is discussed in detail in section 4 of this report.

Following this criteria, for each adoption level, the process for determining the installed capacity of photovoltaic generator per costumer is shown in Figure 9. The known values are annual demand (D) and the PV sizing (%) annual energy is determined to be generated by the photovoltaic (G). From the customer location, average daily radiation (R) of the measurement station nearest (base PVGIS data [8]) is taken and power (P) of the generator is determined using the data of a photovoltaic panel standard (15% overall, 1.3 m2 and 200 Wp).

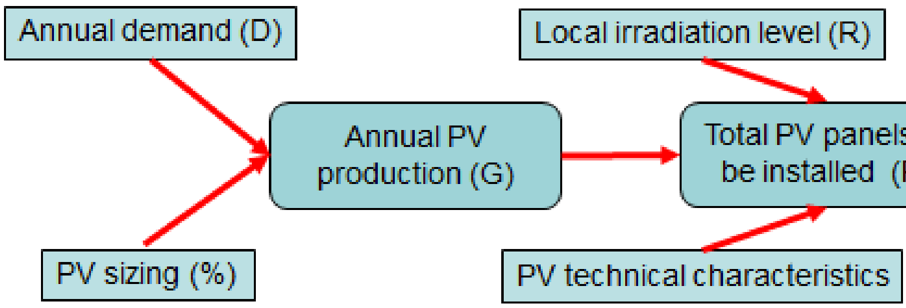



*Figure 9. Process for determining the photovoltaic power installed*

For example, for a LV consumer type with an annual demand of 3500 kWh [9], the peak power of the PV generator to be installed, for instantaneous consumption hypothesis would be 0.8 kWp in Murcia, 0.8 kWp in Madrid and 1.2 kWp in Bizcay. In the case of Murcia and Madrid the result is the same because the annual radiation average is very similar (0.00578 MWh / m2 · Murcia day and 0.00566 MWh / m2 ·Madrid day), while for power is greater in Bizcay having less radiation available (0.00384 MWh / m2 · day). Similarly, if the installation is sized according the hypothesis of deferred consumption, 1.8 kWp would be required to Murcia and 2.6 kWp to Madrid and Biscay.

### 2.1.3 Dimension 3: Geographic concentration

To analyze the impact on losses of photovoltaic generation realistically, it is necessary to note that the development of this generation does not have to be homogeneously, that is, there may be areas of the network where there are a greater number of photovoltaic installations than in others. This study captures this consideration by the known geographic concentration.

A rigorous calculation of the effect of different spatial concentration of consumption should have data per each type of housing located on each LV node of the network and the type of installation of each MV costumer. As these data are not available, so this study has been consider different scenarios of concentration following the procedure below.

The geographic concentration defines how photovoltaic generation which is geographically located within the network by considering the following cases: random, disperse, low, moderate, strong and extreme

- Geographic concentration random, PV generators are randomly distributed among all network loads. Thus, areas where higher consumption, will have greater PV concentration.

- Disperse scenario, each network area will have a similar level of penetration, not dependent on the number of consumers present in the areas.

- For the following levels (low to extreme), it is necessary to use a criterion to define the geographic concentration level of photovoltaic generators. This concentration is carried out at area level and depending on the load density (MWh / km2). Thus, it is considered that areas with *lower demand per km* are rural areas, which have more available space to locate photovoltaic generation; and *higher demand per km* are considered urban, with more limited space.

To assign photovoltaic power according to the geographic concentration a statistical function (exponential distribution) is used. Statistical functions are widely used to characterize or modeling all type of outcome and patterns. According to the exponential distribution, the generators will be located within the network. The cumulative distribution function (CDF) of an exponential distribution is represented by the following equation:

$$p = 1 - e^{-\lambda x}$$

The value of λ parameter defines the curvature of the exponential function and the inverse of the average of the distribution. Thus, defining four different values of λ are obtained four geographic concentration scenarios, which we call low, moderate, strong and extreme. On the other hand, the value of x variable corresponds to the load density per area and the result p is delimited between 0 and 1.

**Definition of parameter λ**

The λ parameter defines the exponential function, as shown in Figure 10. Thus, assign different levels of concentration photovoltaic generation in areas of different density requires only determine different values of λ.

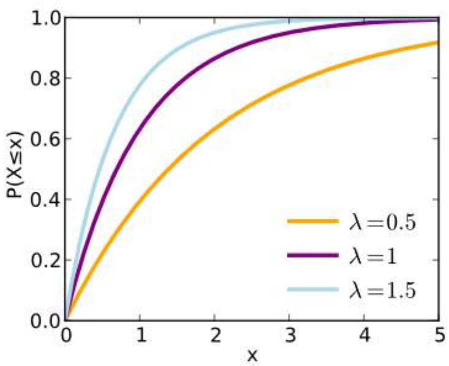



*Figure 10. Cumulative exponential distribution function*

The following scenarios of geographic concentration are defined:

- LOW degree: 63% of the DG is located at 50% of the areas with lower density (probability that "x" is less than or equal to 0.5).
- MODERATE degree: 74% of the DG is located at 50% of the areas with lower density.
- STRONG degree: 86% of the DG is located at 50% of the areas with lower density.
- EXTREME degree: 98% of the DG is located at 50% of the areas with lower density.[1]
- EXTREME degree: 98% of the DG is located at 50% of the areas with lower density

| Degree | Average | Lambda | p(x<=0,5) |
|---|---|---|---|
| Low | 50,0 | 0,0200 | 63% |
| Moderate | 37,5 | 0,0266 | 74% |
| Strong | 25,0 | 0,0400 | 86% |
| Extreme | 12,5 | 0,0800 | 98% |

*Table 5. Values of different geographic concentration degrees*

The figure 11 shows the cumulative probability of different geographic concentration degrees including disperse corresponding to a uniform distribution. These distributions correspond to Murcia case. For other cases or regions can vary according to the densities of the areas to be analyzed.

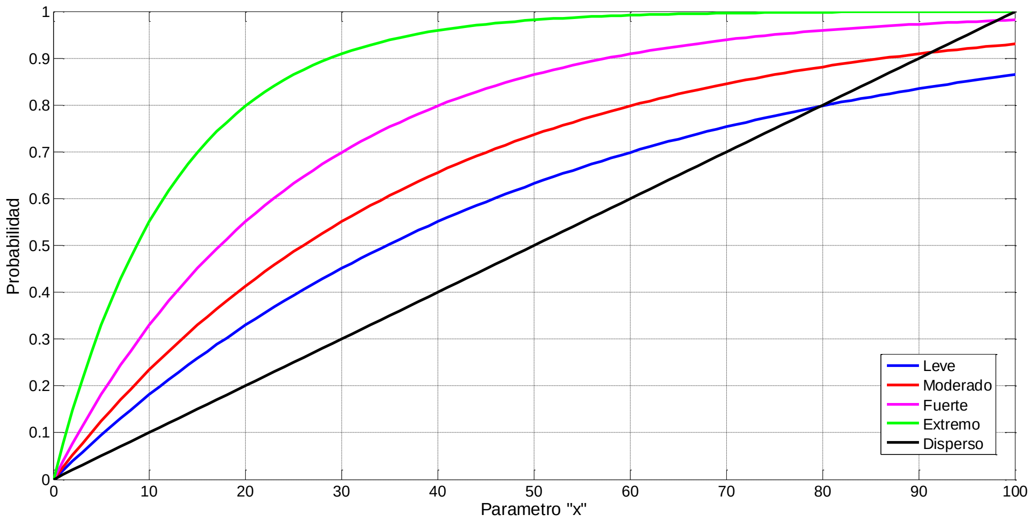



*Figure 11. Distributions for different geographic concentration degrees for Murcia case*

The advantages of using this type of modeling are:

- Establish a concentration concise pattern with different degrees.
- Allows different PV penetration levels in each area, avoiding certain areas remain without PV generation, which is not realistic.
- Allows comparison between different regions, cases and penetration levels since the definition of geographic concentration degrees (low, moderate, strong and extreme) do not change from case to case and are standardized.

[1] Thus the extreme case would correspond to the assumption of 50% of the less dense areas are non-urban areas and in those where consumption takes place almost entirely.

## 2.2 Allocation Process of PV generators

Once the three dimensions are defined to create the photovoltaic self-consumption scenarios, it is necessary to determine the criteria for assigning the PV generator to MV and LV networks customers. This criterion is based on assigning the photovoltaic generators to customers in different areas of the network according to the function corresponding exponential distribution. To do this, smaller areas are arranged at higher density and are assigned a value "z" distributed between 0 and 100, depending on their position in the organization. That is, if there are 20 areas with lower density area will get a z = 0, the following will be z = 5 and so on until 100.

Subsequently, random numbers that follow the exponential distribution to be applied depending on the degree of geographical concentration corresponding to stage dimensioning are generated. That is, you get a random parameter value "x" that corresponds to the area where the generator is located. This is accomplished using the inverse of the exponential cumulative distribution function and generating numbers uniformly distributed between 0 and 1 for the parameter p. This function responds to the following equation:

$$x = \frac{-\ln(1-p)}{\lambda}$$

This approach obtained the value "x" related to the closest value "z", which corresponds to an area.

To summarize, the procedure for allocating photovoltaic generators in each scenario consists of the following steps:

1. The load density is calculated for each area of the MV network
2. The areas are sorted according to their density demand increasing order
3. A value "z" is assigned from 0 to 100 corresponding to the position in the ordering performed in step 2
4. A random number is generated between 0 and 1 (p parameter)
5. The value "x" is obtained by using the inverse of the exponential distribution function, using the λ value corresponding to the geographic concentration scenario to be created (dimension 3).
6. The area with the "z" value closest to "x" value is selected
7. A random load within the selected area in the previous step is selected, and then a PV generator is assigned. The installed power of the PV generator depends on the PV sizing (dimension 2).
8. That load is marked as selected to prevent the system remaps another PV generator.
9. Check if all loads in same area have been selected. In this case, the entire area has demand consumption, so it is eliminated from the process of assigning photovoltaic generators.
10. Determine the PV self-consumption percentage in relation to all network demand. If this value is below the adoption level of the stage to create (dimension 1), the allocation process generation (back to point 2) is continued. If it has reached the desired level of adoption, then the establishment of scenario has been completed.

## 2.3 Assessment of annual energy losses

For the assessment of annual energy losses in each scenario has been set the reference year on 2014. To study have seen eight days type for this year: a workday and a holiday one for each of the four seasons of the year. These reference days of each season correspond having a similar average demand.

For each of the 24 hours a day, Iberdrola has provided the average hourly demand for each customer of the three MV network regions studied. This information is available as a RAW file format for each hour of 8 days for Murcia, Madrid and Biscay Networks. These files have been modified to each of the 132 scenarios studied to include corresponding to each generation of PV generation each scenario.

The generation was calculated from hour irradiation corresponding to the average of the month of each studied days. This information was obtained from PVGIS data base, using information from the measurement station closest to PV generator, from the geographical coordinates of the costumer with self-consumption. In Figure 12 shows the average radiation time is displayed of July in Molina de Segura (Murcia).

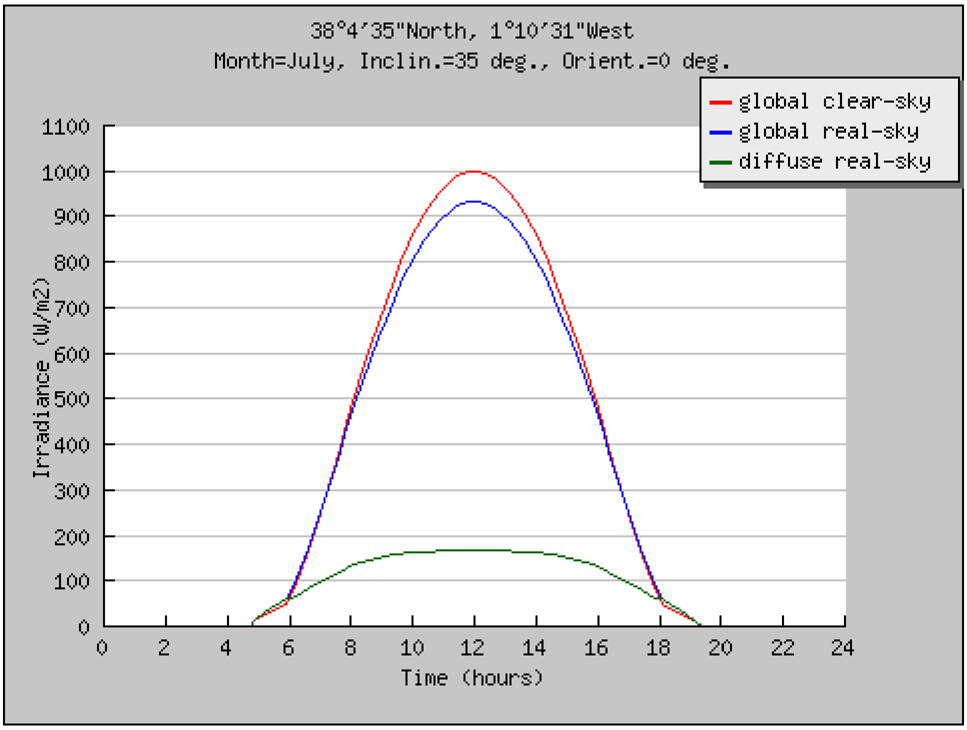



*Figure 12. Irradiation hourly average for July*

The annual power losses in each area of network (Murcia, Madrid and Biscay) have been obtained analyzing load flow with PSS/E software tool, following the next described procedure:

1. A total of 132 photovoltaic generation scenarios for the entire MV network, for each day and hour analyzed, in total 25,344 flows load are resolved. For each hour is stored the flow of active and reactive power at the HV nodes of HV / MV transformers that feed each of the network areas and all nodes of LV substation. The hourly losses are calculated and listed in Excel spreadsheets for further analysis, along with voltages of all nodes.

2. A total of 132 photovoltaic generation scenarios for the entire HV network, A total of 132 photovoltaic generation scenarios for the entire MV network. In each node of HV network where HV/MV transformers are connected an equivalent load with the active and reactive power calculated in the previous step, the load flow of the MV network for scenario generation, day and corresponding hour. The existing generation in HV network it is reduced by the same amount generated in MV and LV by photovoltaic generation, by re-dispatch proportionally to the power of each PV generator. The hourly energy losses are calculated and listed in Excel spreadsheets for further analysis, along with voltages of all network nodes.

3. For each of 40 LV networks studied, the demand is scaled from the calculated active and reactive power in the load flow solution of the MV network for the case without generation. The 132 photovoltaic generation scenarios are created following the procedure specified in paragraph 2.3, with the difference that the load density is used by LV lines to define the degree of geographical concentration. The 132 scenarios are solved for each of the days and hours analyzed, in total 25,344 additional load flows.

4. After obtaining the hourly losses in each scenario, annual losses for each network level are estimated. For HV and MV networks, which include 100% of demand, the annual losses are calculated form the losses of each of the eight days studied by the following formula is obtained:

$$Annual\ losses = 26 * \sum_{1}^{4} holiday\ losses + 65 * \sum_{1}^{4} workable\ days\ losses$$

For the LV network is followed an alternative procedure, since there is no 100% of the modeled demand. The study estimated the annual loss for the 40 networks analyzed using the above formula and the coefficient losses obtained by dividing the annual losses and the annual demand of 40 networks. The energy losses of the 100% network are estimated by multiplying this ratio of losses by the annual demand of the LV network, obtained from load flows in MV network, which has modeled all substations which powered the LV loads.

Both load flow calculation and subsequent analysis of the data has been automated using Python scripts for PSS/E, and VBA macros for Excel. The total execution time ranges from 28 hours to the Murcia area network and more than 40 hours for the Madrid area network. The figure 13 shows the calculation procedure followed and the most illustrative magnitudes are given concerning data management in each area through network.

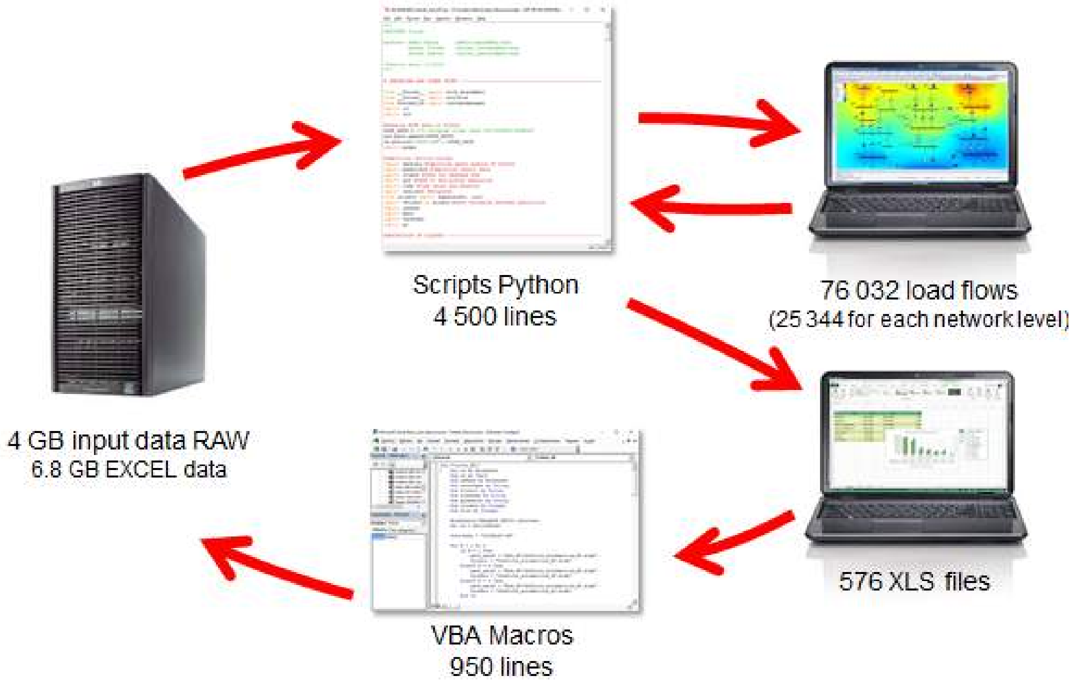



*Figure 13. Calculation Procedure*

## 2.4 Base Case. Model validation

To validate the modeling of each network zone and the procedure for calculating energy losses is resolved case basis for each network. This base case corresponds to the situation of demand and distributed generation network in 2014, in other words, not including photovoltaic generation associated with self-consumption.

The tables 6-8 show the results of the model for MV and LV distribution on Murcia, Madrid and Biscay respectively. The estimated demand was made from the complete model of the MV network, so the demand for the MV network is net (not included energy losses), while demand for LV network is gross (included energy losses).

The network gross demand in 201 was supplied by Iberdrola, and has been compared to the estimated gross demand, which corresponds to the total demand in MV and LV plus losses calculated for the MV network. As shown, the error between the data calculated by the model and the data supplied is between 3.71% for Madrid network and 0.69% for Biscay network.

The model developed for each network zone only estimates the value of technical losses and does not include effects such as nonlinearity of loads, imbalances between the demand for each phase, changes in demand within each hour, etc., the margin of error is within the expected value of losses for such networks. Therefore, it is considered that the model is valid to estimate the influence on network losses associated with distributed generation facilities of self-consumption connected to the MV and LV network.

| | Demand<br>GWh | Losses<br>GWh | Loss rate (%) |
|---|---|---|---|
| LV Network | 3121.36 (1) | 124.43 (2) | 4.15% |
| MV Network | 2977.35 (3) | 120.63 (4) | 1.98% |
| Total (MV + LV) | 6098.71 (5=1+3) | 245.06 (6=2+4) | 4.10% |
| Estimated Gross Demand | 6219.34 (7=5+4) | | |
| Gross Demand 2014 | 6370.30 (8) | | |
| Estimation Error (%) | 2.34% | | |

*Table 6. Energy losses of distribution network in Murcia. Base case*

| | Demand<br>GWh | Losses<br>GWh | Loss rate (%) |
|---|---|---|---|
| LV Network | 8750.60 (1) | 168.42 (2) | 1.96% |
| MV Network | 6197.16 (3) | 145.63 (4) | 0.97% |
| Total (MV + LV) | 14947.76 (5=1+3) | 314.05 (6=2+4) | 2.12% |
| Estimated Gross Demand | 15093.39 (7=5+4) | | |
| Gross Demand 2014 | 15675.35 (8) | | |
| Estimation Error (%) | 3.71% | | |

*Table 7. Energy losses of distribution network in Madrid. Base case*

| | Demand<br>GWh | Losses<br>GWh | Loss rate (%) |
|---|---|---|---|
| LV Network | 2556.71 (1) | 43.04 (2) | 1.71% |
| MV Network | 267.57 (3) | 35.62 (4) | 1.26% |
| Total (MV + LV) | 2824.28 (5=1+3) | 75.64 (6=2+4) | 2.83% |
| Estimated Gross Demand | 2859.9 (7=5+4) | | |
| Gross Demand 2014 | 2879.86 (8) | | |
| Estimation Error (%) | 0.69% | | |

*Table 8. Energy losses of distribution network in Biscay. Base case*

# 3 Results

In this chapter analyzes the main results of the technical losses calculated of networks of Murcia, Madrid and Biscay for 132 self-consumption scenarios resolved. The structure of each subsection is similar. The context of the results, first installed photovoltaic generation data is showed for each self-consumption scenario and each adoption level, then the hourly generation for each studied seasons is analyzed. Next, the overall results for the entire network are displayed and disaggregated according the voltage level from HV to LV network. Finally, a detailed result is showed with some hourly examples of different analyzed days.

## 3.1 Murcia Network

### 3.1.1 Photovoltaic generation

The table 9 shows the PV self-consumption installed power in MV and LV network in Murcia for each level of adoption and consumption scenario analyzed. Additionally, the network peak demand is indicated for summer and winter, providing context for the volume of connected PV generation.

The installed photovoltaic generation can be exceed the peak demand from an adoption level of self-consumption of 90%, in case of Instantaneous consumption, while for the deferred consumption case, occurs in a lower adoption level, 40%.

For a 100% adoption of self-consumption demand, the PV installed capacity would exceed 18% of peak demand scenario for deferred consumption case, and the 195% for deferred consumption one.

However, a photovoltaic generator, the actually produced power depends on the incident radiation, therefore, in figures 14 and 15 shown, for the case of 100% self-consumption adoption, which is the hourly photovoltaic generation for daily average radiation of each season analyzed in the study. In this case is observed that the PV installation cannot achieve to generate all installed power, because in the rush hour will not reach the 1000 W/m2 of radiation, which is the value for which the peak power of PV panel.

<table>
<tr><th rowspan="2">Adoption Level</th><th colspan="2">Installed capacity PV (MWp)</th><th colspan="2">Peak Demand (MW)</th></tr>
<tr><th>Instantaneous consumption</th><th>Deferred consumption</th><th>Summer</th><th>Winter</th></tr>
<tr><td>10%</td><td>117</td><td>294</td><td rowspan="10">997</td><td rowspan="10">996</td></tr>
<tr><td>20%</td><td>235</td><td>589</td></tr>
<tr><td>30%</td><td>353</td><td>883</td></tr>
<tr><td>40%</td><td>470</td><td>1176</td></tr>
<tr><td>50%</td><td>588</td><td>1472</td></tr>
<tr><td>60%</td><td>707</td><td>1768</td></tr>
<tr><td>70%</td><td>825</td><td>2064</td></tr>
<tr><td>80%</td><td>942</td><td>2355</td></tr>
<tr><td>90%</td><td>1060</td><td>2651</td></tr>
<tr><td>100%</td><td>1177</td><td>2940</td></tr>
</table>

*Table 9. Installed capacity PV of self-consumption. Murcia*

The table 9 shows no big differences between the spring and autumn. The maximum radiation is during the summer months and the minimum for the winter months. The maximum radiation in summer is 25% higher than winter rush hour.

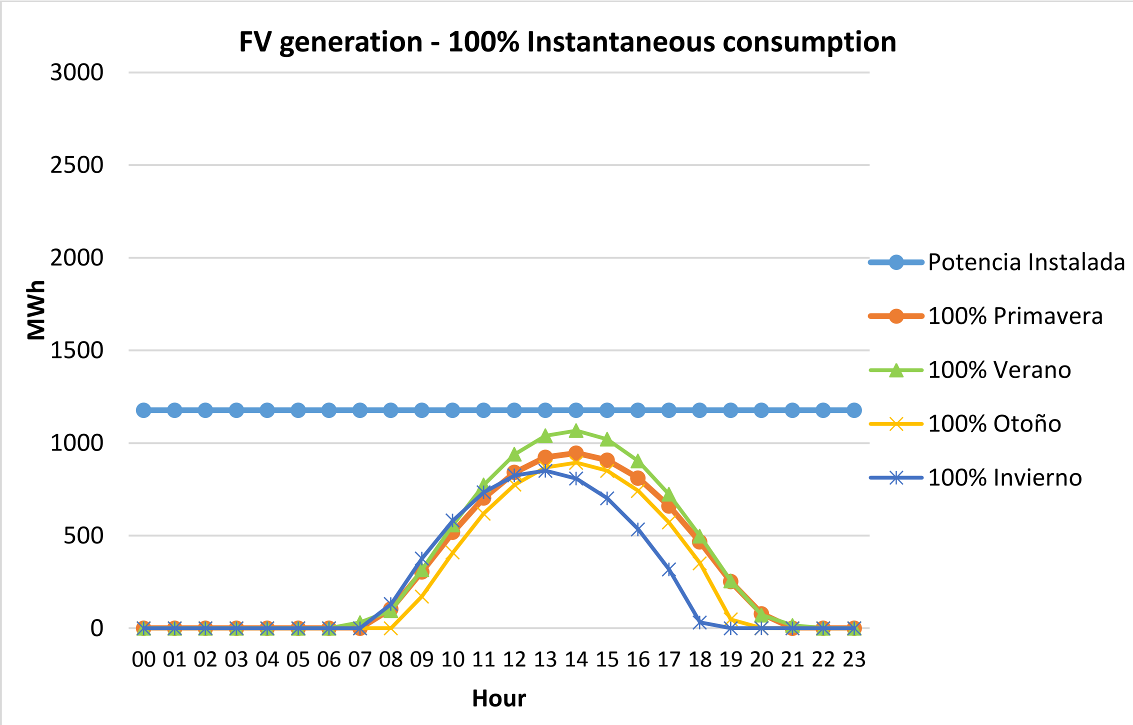



*Figure 14. Installed capacity and PV seasonal generation in Murcia. 100% Instantaneous consumption.*

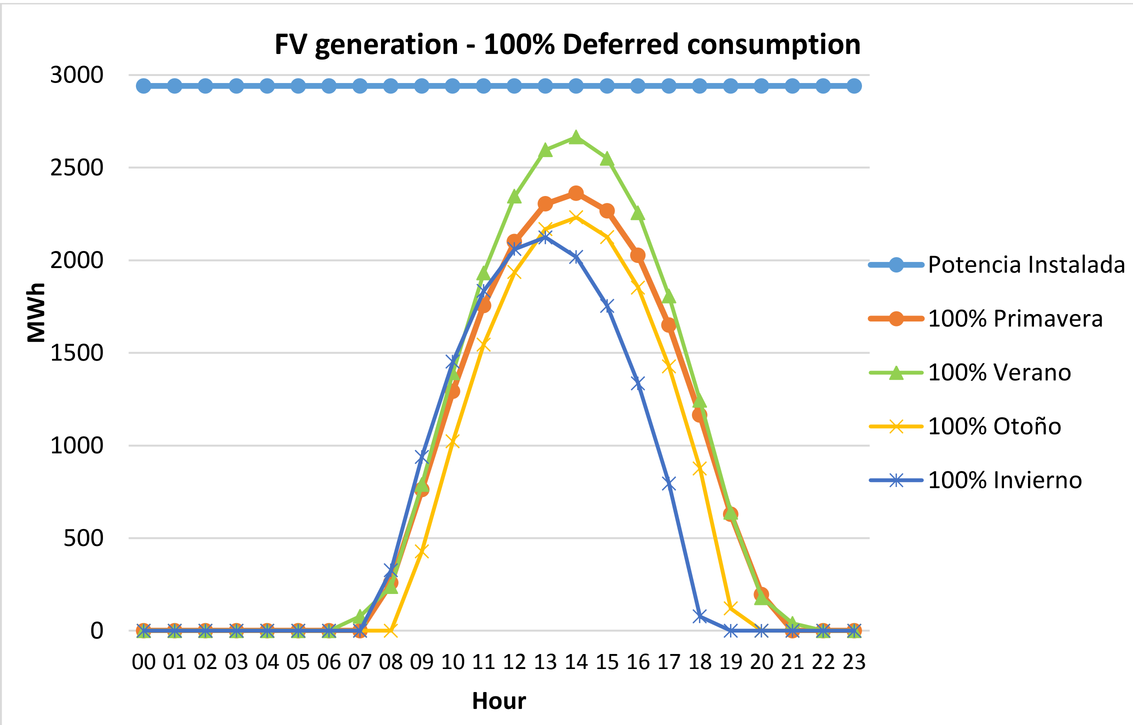



*Figure 15. Installed capacity and PV seasonal generation in Murcia. 100% deferred consumption*

### 3.1.2 Annual energy losses

The figure 16 shows the variation of annual energy losses throughout the network of Murcia (including the transmission system variation), in relation to the case without self-consumption, for each adoption level and geographic concentration scenario studied, when facilities of self-consumption are sized for the Instantaneous consumption case.

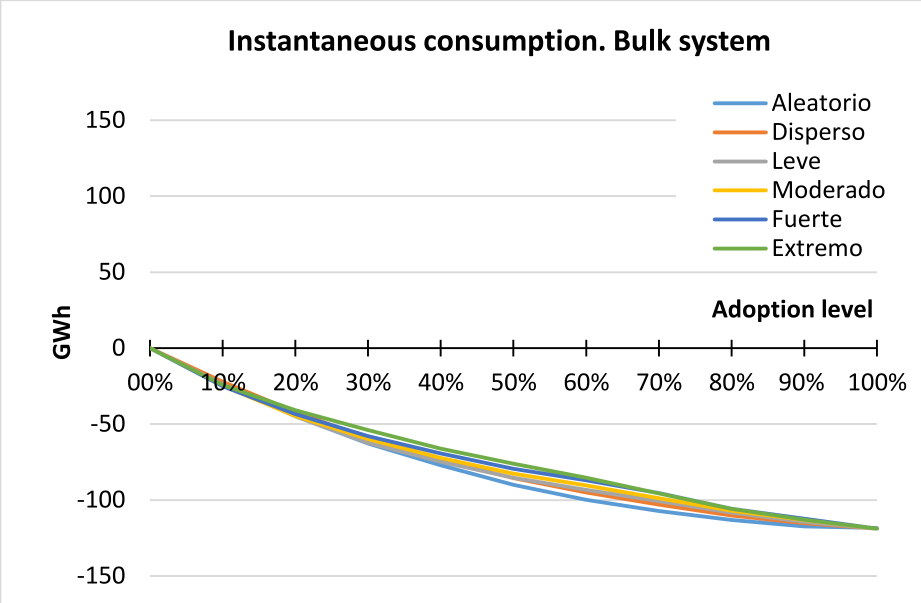



*Figure 16. Total variation of network losses in Murcia. Instantaneous consumption*

In conclusion, the self-consumption connected to MV and LV reduces losses for all adoption levels, the geographic concentration is not significant; and is concentrated for intermediate adoption levels. For the 100% adoption level, the losses are reduced to a minimum of -119 GWh.

The figure 17 shows the variation of annual energy losses throughout the network of Murcia when self-consumption of photovoltaic installations are designed according the deferred consumption case. In this situation, the energy losses decrease between -32 GWh (10% adoption, extreme degree) and -106 GWh (40% adoption, random degree), but tend to increase up to a value of 122 GWh. That is, there is a strong influence of the geographic concentration. The more concentrated self-consumption takes place in the network of Murcia, the negative influence on the losses is greater, since the reduction on low adoption levels will be lower and before the adoption level will be reached beyond which the losses starting increase.

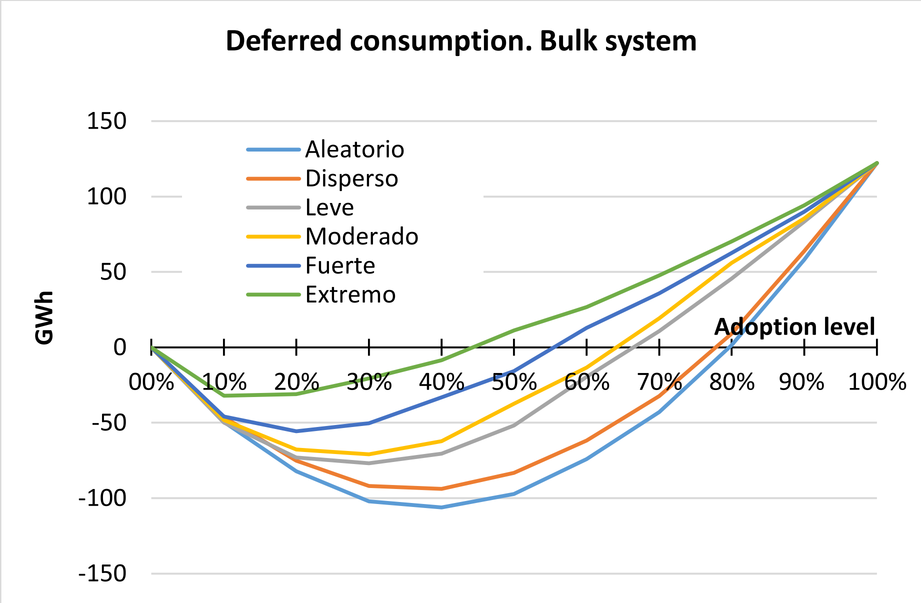



*Figure 17. Total variation of network losses in Murcia. Deferred consumption*

The total losses shown are the sum of the losses considered in each of the three levels of network, in other words, the losses included the variation of losses in the distribution network (low and medium voltage) and also the transmission network losses (high voltage).

The figures from 18 to 20 show the percentage change of losses on the case without photovoltaic self-consumption broken down by network level with the hypotheses of Instantaneous consumption, in order to analyze where the variation of losses occurs. As conclusion, the greatest influence is given on the networks of medium and low voltage.

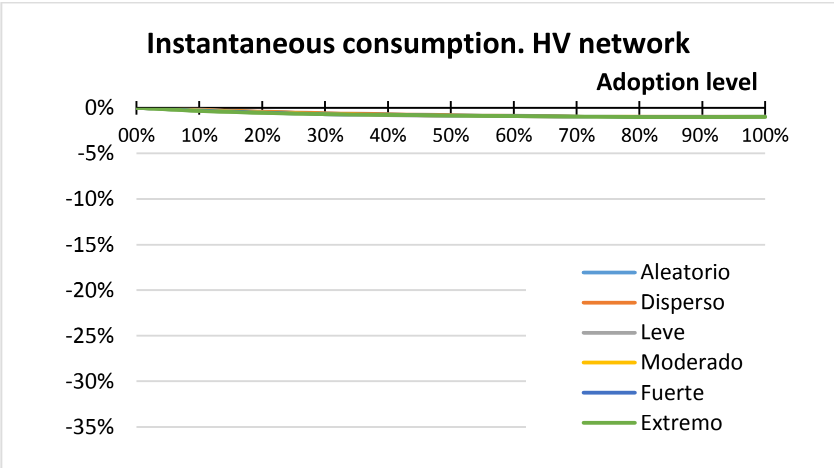



*Figure 18. Percentage change of losses in HV network of Murcia.*

*Instantaneous consumption*

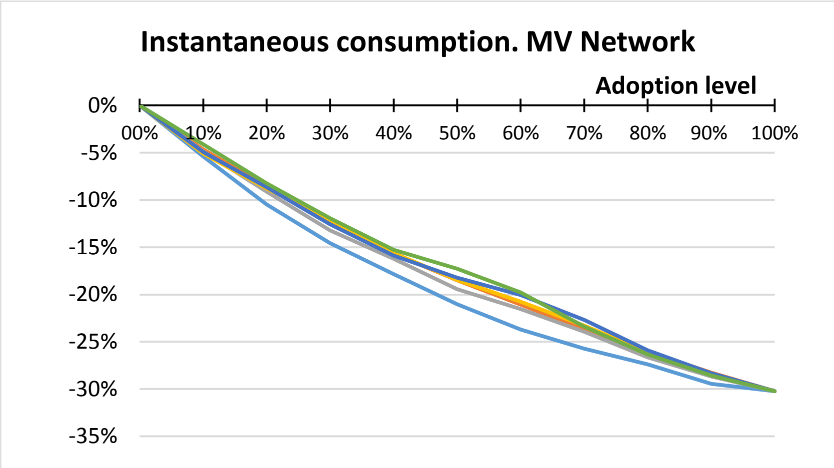



*Figure 19. Percentage change of losses in MV network of Murcia. Instantaneous consumption*

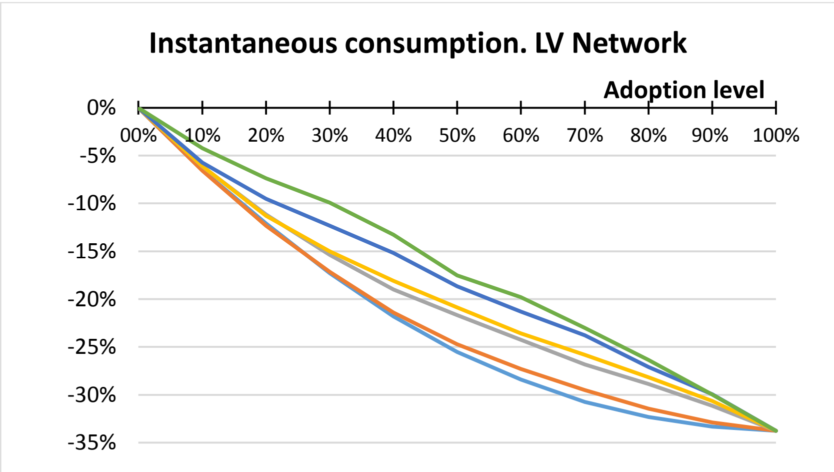



*Figure 20. Percentage change of losses in LV network of Murcia. Instantaneous consumption*

The influence of the Instantaneous consumption on HV networks studied, show how the losses decrease with increasing adoption until the minimum is reached when all the demand in MV and LV is self-consumption. In terms of percentages, the influence on the entire transmission network is small the geographic concentration is not significant.

The behavior of the MV and LV networks is similar to HV network, but the influence on the variation of losses is much higher. With increasing adoption of PV self-consumption, reduce losses reaching a maximum decrease of 30% for the MV network and 34% for LV network when all the demand of the distribution network has adopted self-consumption. In relation to geographic concentration, is concluded that the influence is more for intermediate cases of adoption, being more important in LV network than MV network.

The figures from 21 to 23 are shown the results disaggregated by network levels for the deferred consumption case. As for Instantaneous consumption, the greatest influence is given on MV and LV networks.

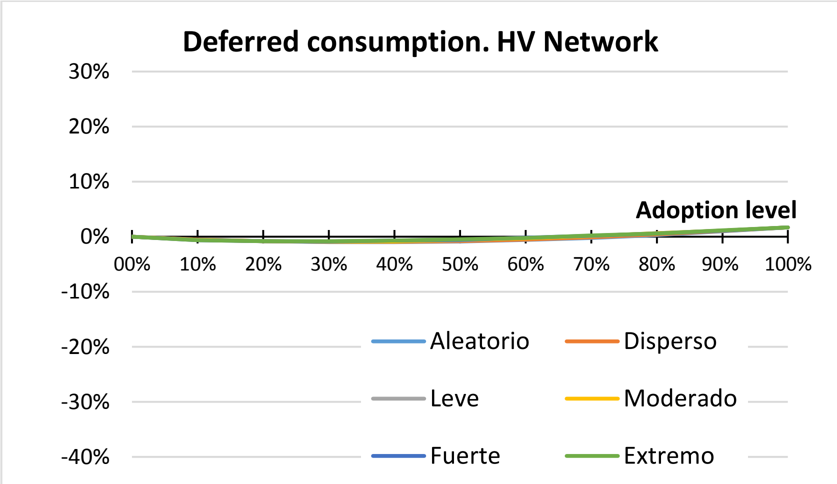



*Figure 21. Percentage change of losses in HV network of Murcia. Deferred consumption.*

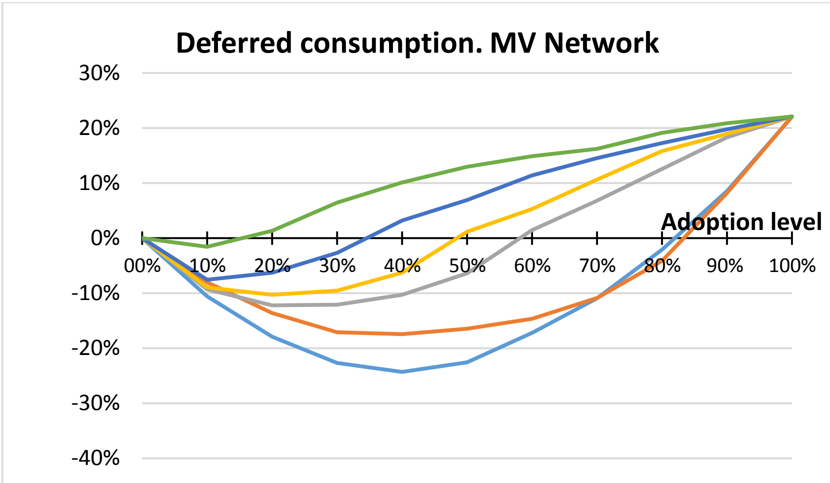



*Figure 22. Percentage change of losses in MV network of Murcia. Deferred consumption.*

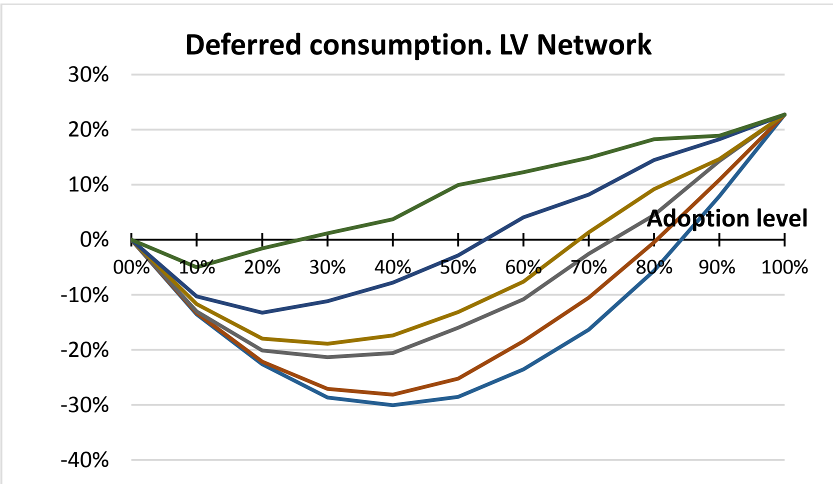



*Figure 13. Percentage change of losses in LV network of Murcia. Deferred consumption*

When the photovoltaic self-consumption facilities are designed for hypothesis of deferred consumption, the influence on the variation of losses at different levels of network is similar. For low adoption levels reduce losses to a minimum, from which the losses increase again with increasing the adoption level.

For HV network, the losses reduce to a minimum of -0.94% (to 40% adoption level with a degree of random geographic concentration). From an adoption level between 65% and 75%, depending on the geographic concentration, the losses increase again to 1.71% when FV adoption is 100%.

For MV and LV networks, the behavior is very similar, being higher percentages of variation of losses for LV to MV. For the MV network losses decrease up to 24%, with 40% adoption level, random geographic concentration, then increase up to 22% with 100% adoption level of self-consumption. For LV network, the minimum is 30% of losses, for the same level of adoption and degree of geographical concentration, and the maximum is 23% with 100% adoption level of self-consumption.

Finally, in all cases when the degree of geographic concentration is greater, the losses reduction is less for the same adoption level of self-consumption and, similarly, the adoption level from which the losses increase is also low.

### 3.1.3 Hourly losses

This section provides an analysis of hourly evolution of the losses for two specific days of the eight analyzed, a working-day of winter and other working-day of summer. The aim is to study in detail the influence of the PV self-consumption in losses for different demand levels and photovoltaic generation.

The analysis is performed for two self-consumption scenarios, Instantaneous and deferred consumption, with similar self-consumed power. Thus, for Instantaneous consumption scenario results for 80% of adoption level, this corresponds to a 32% self-consumption power. For the deferred consumption scenario, the equivalent case of 30% adoption level, his corresponds to a 30% self-consumption power.

In the figures 24 to 29 show the time variation of losses in the HV, MV and LV for each scenario of geographic concentration, in winter (upper graphs) and in summer (lower graphs). The graphics show how the losses are reduced in all scenarios, with a greater reduction in summer, due to the high irradiation than winter.

Regarding the degree of geographic concentration, the HV network is not significant influence, whereas for MV and LV networks is observed a slight influence, as the geographic concentration increase the change losses decrease. This effect is more important in summer than in winter, because of the higher radiation available for the same installed photovoltaic power consumption.

The figures 30 to 35 show the same results for deferred consumption case. The same effects for Instantaneous consumption is reflected, but more marked occur. The influence of geographic concentration degree is significant, leading to increasing losses, both in winter and summer, in MV network for extreme degrees of geographic concentration. In LV network losses come to compensate for extreme degrees of geographic concentration, while the HV always reduced.

Comparing the results for each scenario Instantaneous and deferred consumption, we can conclude that the losses reduction is higher for Instantaneous consumption scenarios and, in turn, increased losses are lower. However, the installed capacity for deferred consumption scenario (Table 9) is greater than Instantaneous consumption scenario. The explanation is due to the different sizing of photovoltaic generators.

Thus, for the scenario of Instantaneous consumption, there are 80% of consumers who have adopted self-consumption option, while for deferred consumption scenario, there are only 30% of consumers with self-consumption. However, the photovoltaic generators power is more than doubled. Being less spread over the network, the effect on the losses is multiplied, especially in scenarios of high geographic concentration.

In conclusion, the losses will be greater if the PV sizing is based on deferred consumption scenario than is adopted by the Instantaneous consumption one, although the annual self-consumption power by prosumers connected to MV and LV network is similar.

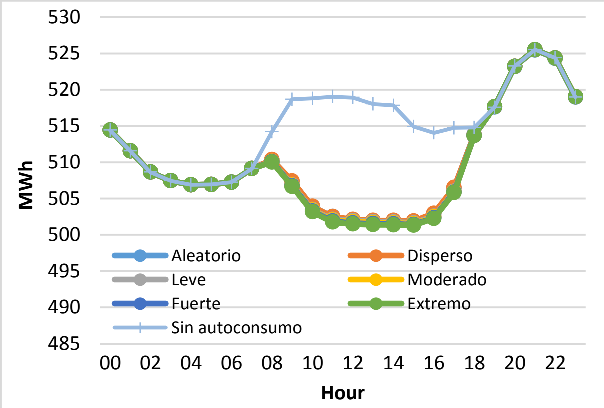



*Figure 24. Time Variation of losses for HV Network, Murcia. 80% Instantaneous consumption. Working day - Winter*

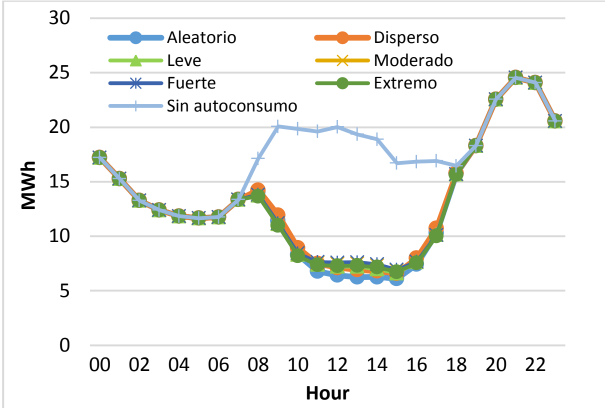



*Figure 26. Time Variation of losses for MV Network, Murcia. 80% Instantaneous consumption. Working day - Winter*

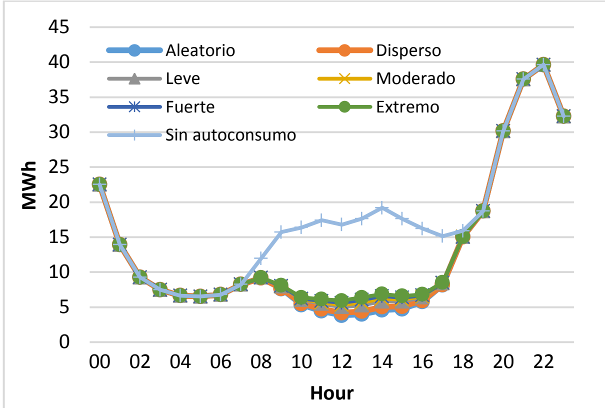



*Figure28. Time Variation of losses for LV Network, Murcia. 80% Instantaneous consumption. Working day - Winter*

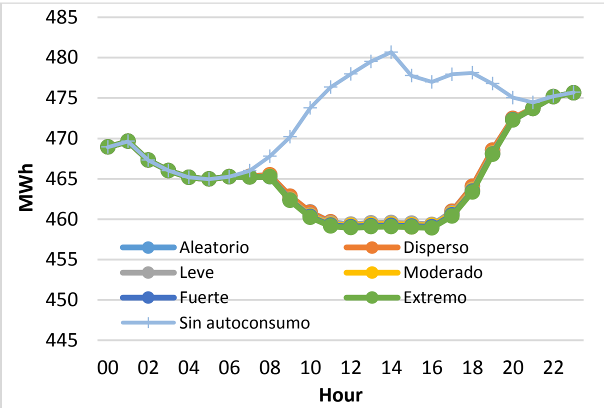



*Figure 25. Time Variation of losses for HV Network, Murcia. 80% Instantaneous consumption. Working day - Summer*

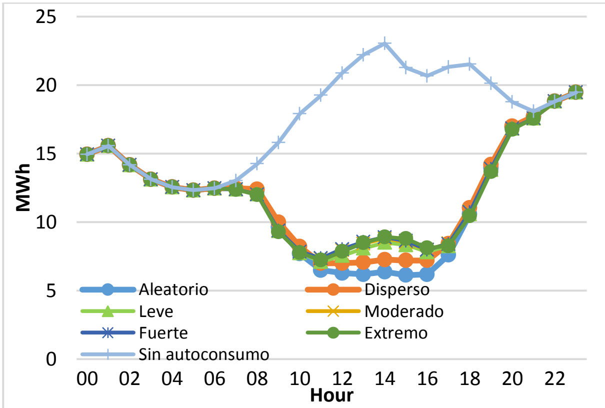



*Figure 27. Time Variation of losses for MV Network, Murcia. 80% Instantaneous consumption. Working day - Summer*

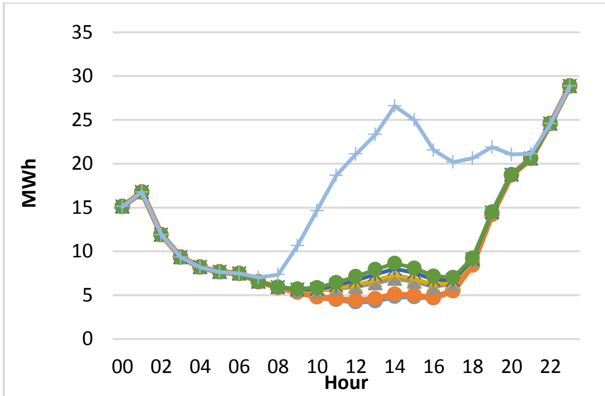



*Figure 29. Time Variation of losses for LV Network, Murcia. 80% Instantaneous consumption. Working day - Summer*

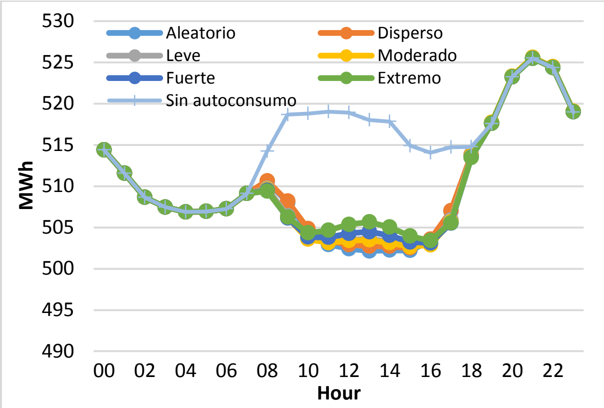



*Figure 30. Time Variation of losses for HV Network, Murcia. 30% deferred consumption. Working day - Winter*

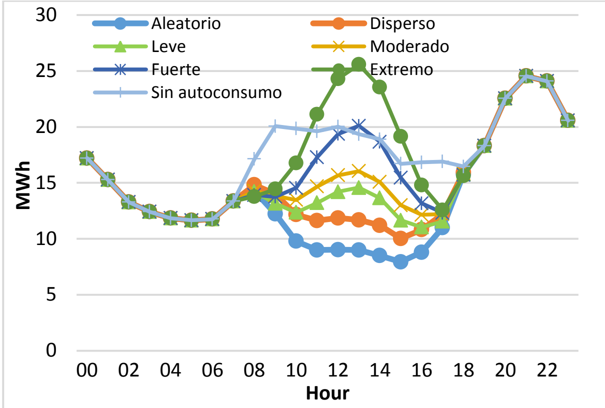



*Figure 32. Time Variation of losses for MV Network, Murcia. 30% deferred consumption. Working day - Winter*

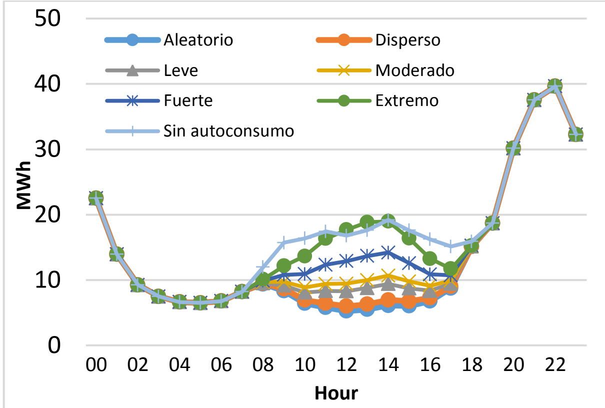



*Figure 34. Time Variation of losses for LV Network, Murcia. 30% deferred consumption. Working day - Winter*

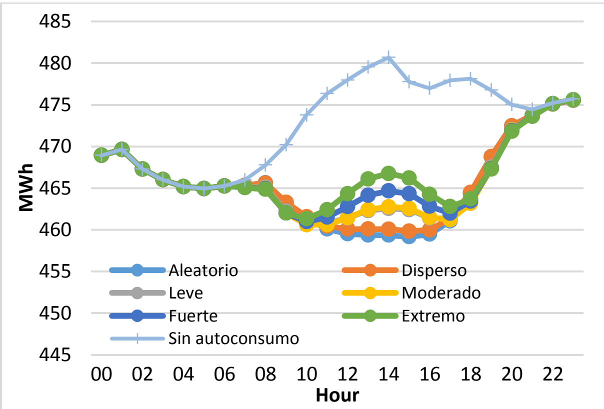



*Figure 31. Time Variation of losses for HV Network, Murcia. 30% deferred consumption. Working day - Summer*

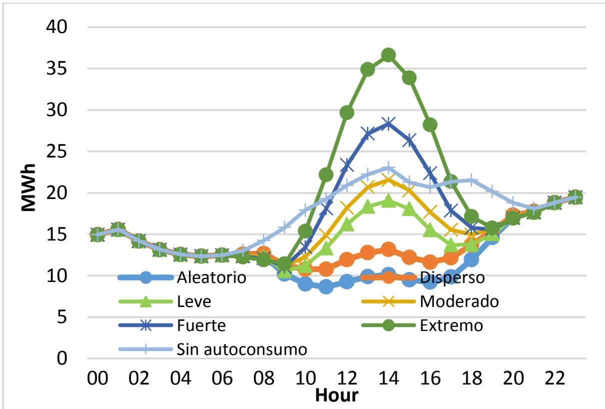



*Figure 33. Time Variation of losses for MV Network, Murcia. 30% deferred consumption. Working day - Summer*

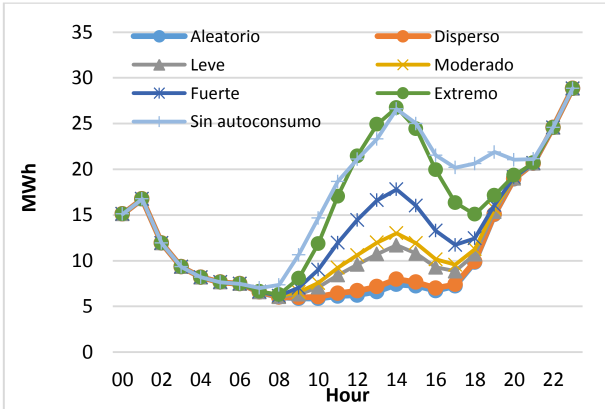



*Figure 35. Time Variation of losses for LV Network, Murcia. 30% deferred consumption. Working day - Summer*

## 3.2 Madrid Network

### 3.2.1 Fotovoltaic generation

The table 10 shows the PV self-consumption power installed in MV and LV network in Madrid for every level of adoption and consumption scenario analyzed, along with the network peak demand in summer and winter.

Similar to Murcia`s case, installed photovoltaic generation exceeds the peak demand from an adoption level of Instantaneous consumption of 80% in summer and 90% in winter. For deferred consumption scenario, peak demand both winter and summer is exceeded for 40% of adoption level.

For a 100% of adoption level of self-consumption demand, the PV installed capacity would exceed by 27% the peak demand summer and 12% in winter, for the scenario of Instantaneous consumption. For deferred consumption scenario, would be greater than 217% in summer and 179% in winter. Compared with Murcia´s case, these values are higher in summer and lower in winter.

| Adoption Level | Installed capacity PV (MWp) | | Peak Demand (MW) | |
|---|---|---|---|---|
| | Instantaneous consumption | Deferred consumption | Summer | Winter |
| 10% | 295 | 735 | 2320 | 2642 |
| 20% | 590 | 1417 | | |
| 30% | 886 | 2211 | | |
| 40% | 1180 | 2949 | | |
| 50% | 1475 | 3686 | | |
| 60% | 1771 | 4424 | | |
| 70% | 2066 | 5162 | | |
| 80% | 2361 | 5895 | | |
| 90% | 2657 | 6633 | | |
| 100% | 2948 | 7367 | | |

*Table 10. Installed capactiy PV of self-consumption. Madrid*

The power actually discharged into the grid by self-consumption facilities showed in Figures 36 and 37 for the 100% case of self-consumption adoption, average daily irradiation are analyzed for each of the four seasons. As for the case of Murcia, there are no major differences between the spring and autumn; however, between the summer and winter, the difference is greater, reaching a value 38% higher in summer.

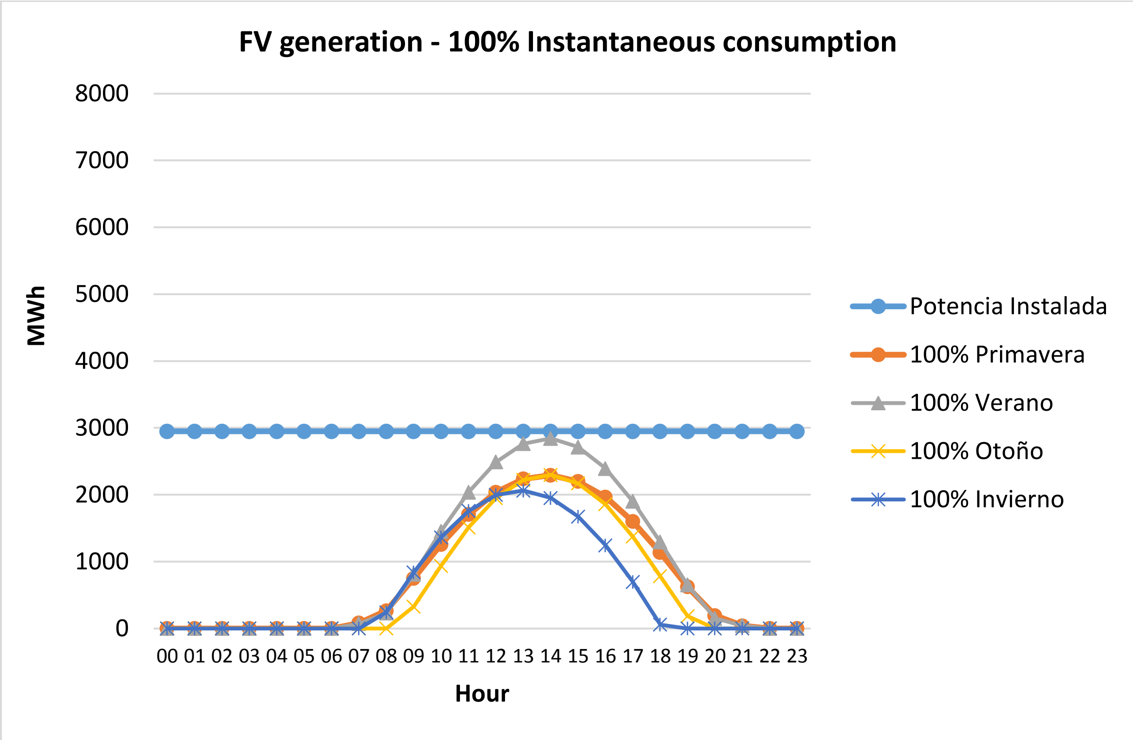



*Figure 36. Installed capacity and PV seasonal generation in Madrid. 100% Instantaneous consumption*

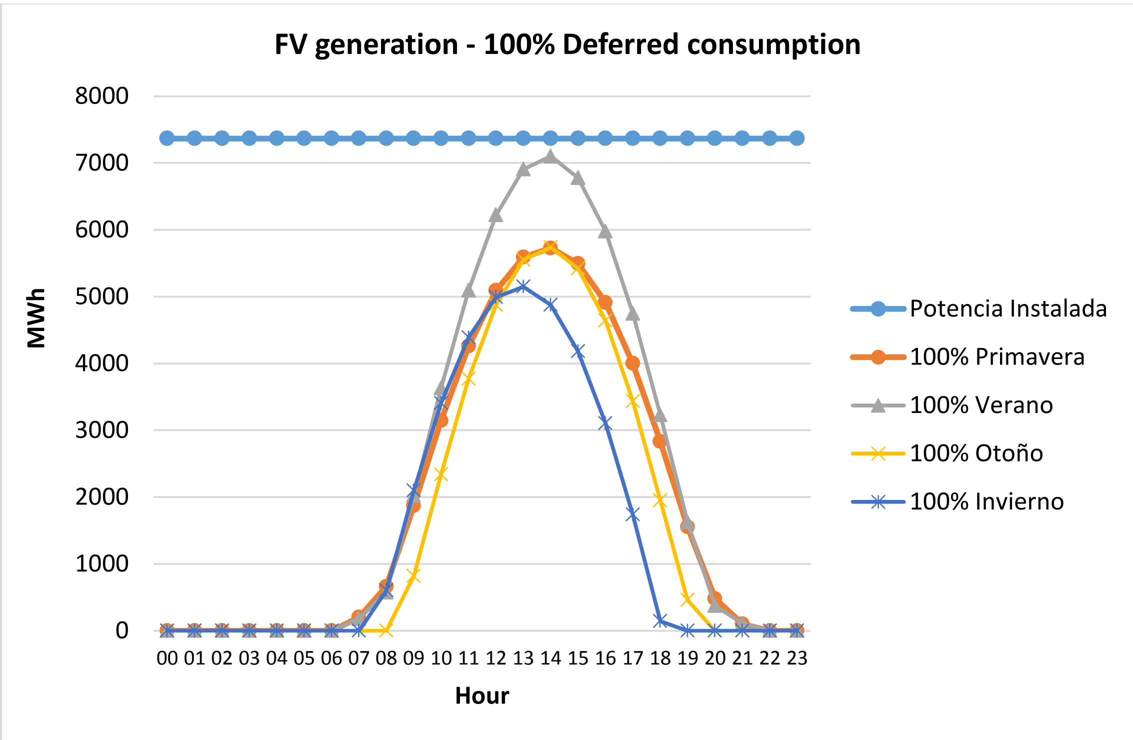



*Figure 37. Installed capacity and PV seasonal generation in Madrid. 100% Deferred consumption*

### 3.2.2 Annual energy losses

The figure 38 shows the annual variation losses throughout the network of Madrid (including variation in transmission network), regarding the case without consumption, for each adoption level and geographic concentration scenario studied, when facilities of self-consumption are sized for Instantaneous consumption case.

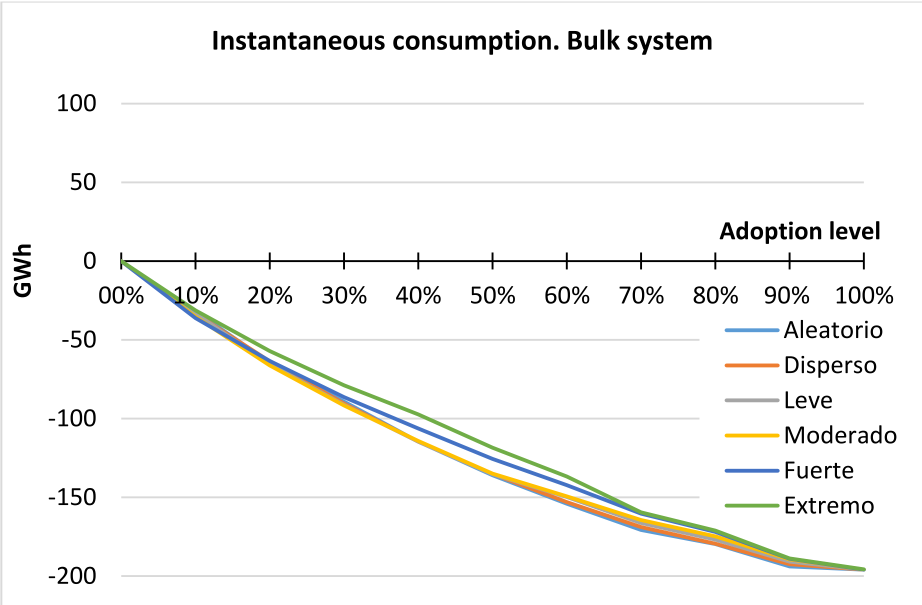



Figure 38. Total variation of network losses in Madrid. Instantaneous consumption

The losses behavior is similar for the case analyzed in Murcia. The MV and LV consumption reduces losses with all adoption levels, being influenced by the geographical concentration degree, on small and intermediate adoption levels. The losses decrease up to a mminimum of -196 GWh.

The figure 39 shows the variation losses of annual energy losses throughout the network of Madrid with deferred consumption scenario, the same behavior as in the case of Murcia, although the losses decrease more significantly for higher adoption levels of self-consumption, and increased to 100% of adoption level is slower

Thus, the losses decrease between -54 GWh (20% adoption level with extreme geographic concentration degree) and -161 GWh (40% adoption level with a random geographic concentration degree), to increase again up to 87 GWh. Compared to Murcia, the geographic concentration is very significant, although, higher adoption levels can be achieve before losses increase above the scenario without self-consumption. In conclusion, as in Murcia case, with more concentration of PV self-consumption in Madrid´s network; the negative impact on the losses is greater.

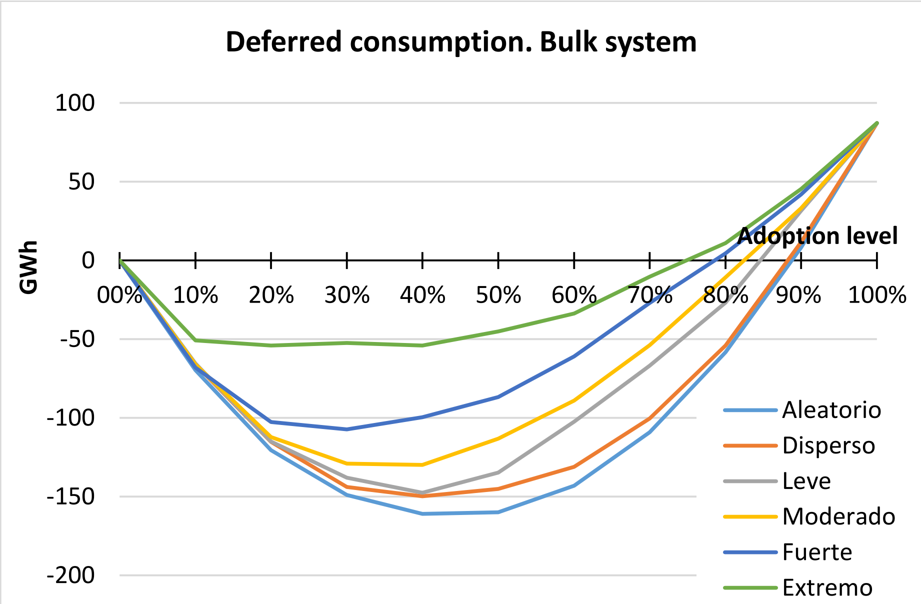



Figure 39. Total variation of network losses in Madrid. Deferred consumption

In Figures 40 to 42 show the percentage change in losses on the case without photovoltaic self-consumption broken down by network-level for the instantaneous consumption case. The behavior is similar to Murcia results; the variation of losses is much higher in the networks of MV and LV, than HV, although in all scenarios studied by increasing the level of adoption losses all network levels decrease.

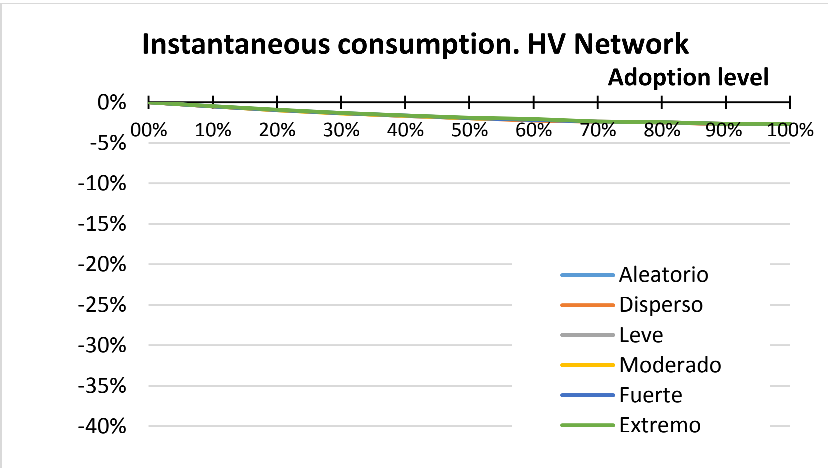



Figure 40. Total variation of losses in HV networks of Madrid. Instantaneous consumption

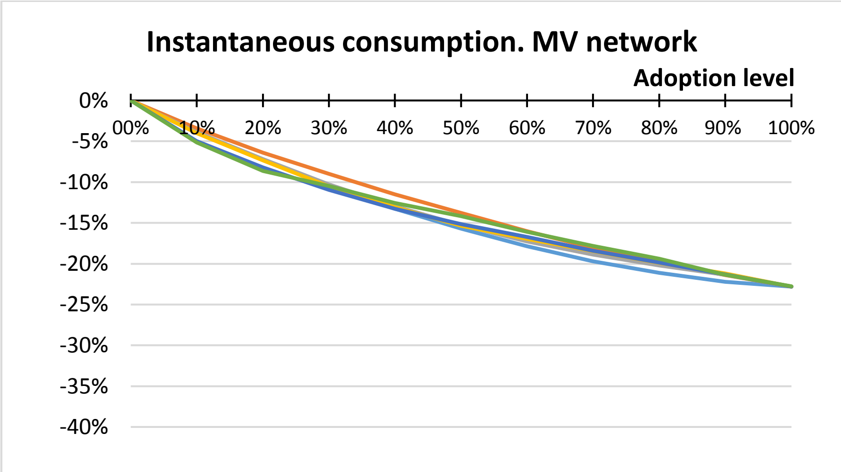



Figure 41. Total variation of losses in MV networks of Madrid. Instantaneous consumption

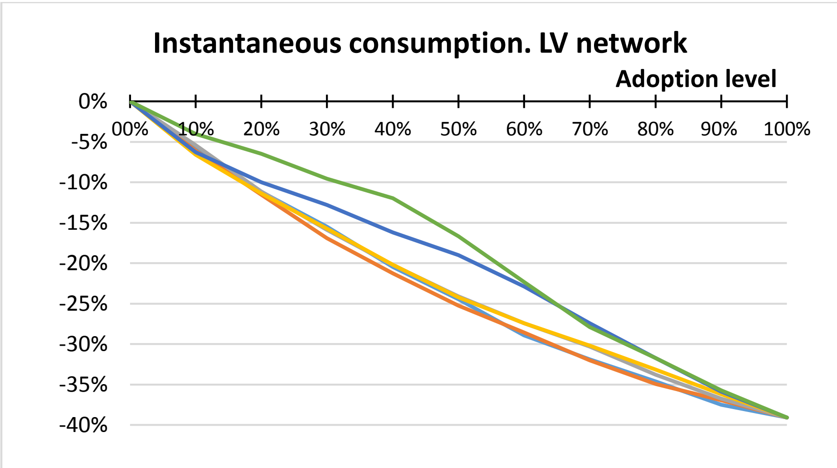



Figure 42. Total variation of losses in LV networks of Madrid. Instantaneous consumption

For the HV network the percentage of change losses is high than Murcia case. This is because the network of 15 kV MV Madrid is not directly connected to the transmission network, but there is an intermediate meshed network of 45 kV. This network has been included in the PSS/E model of Madrid.

For networks of MV and LV, to increase adoption of FV consumption, losses decrease reaching a maximum decrease of 23% for MV network and 40% for LV network when all the demand of the distribution network has adopted self-consumption. That is, LV network has higher weight losses in Madrid than in Murcia.

In relation to geographical concentration of FV generation degree, seen as having more influence for intermediate adoption levels, being more important in LV network than in MV network.

In Figures 43-45, the study results disaggregated level network for deferred consumption case, obtaining a similar result to Murcia results. When photovoltaic self-consumption facilities are designed for a deferred consumption hypothesis for low adoption levels the losses reduce to a minimum, from which point the losses increase again according increasing the level of adoption.

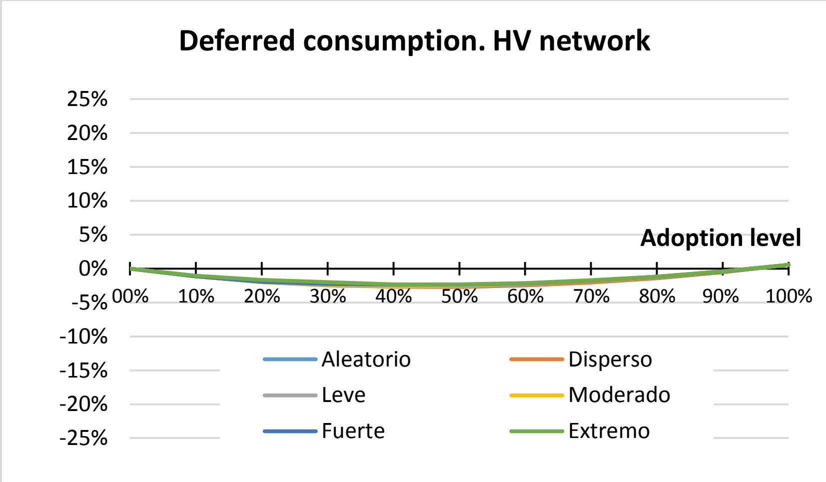



Figure 43. Total variation of losses in HV networks of Madrid. Deferred consumption

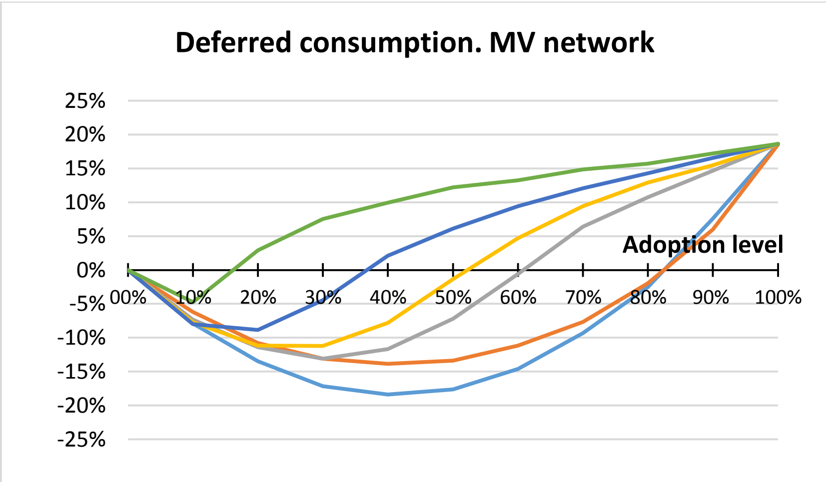



Figure 44. Total variation of losses in MV networks of Madrid. Deferred consumption

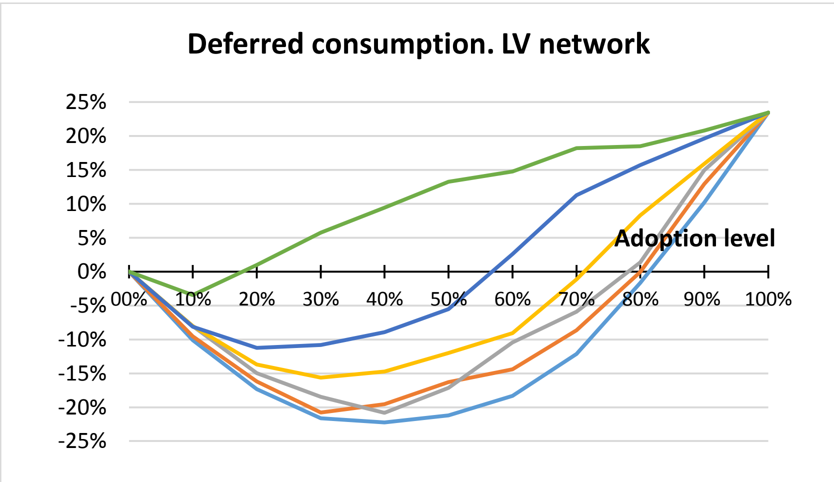



Figure 45. Total variation of losses in LV networks of Madrid. Deferred consumption

For the HV network, reduce losses to a minimum of -2.60%, for 50% adoption level of a low degree of concentration, increased again to 0.56% when the level is exceeded adoption 90%. Unlike the case of Murcia, where the greatest reduction in losses for the stage random concentration of the HV networks in Madrid get is beneficial for losses slightly concentrating photovoltaic generation in MV and LV.

For MV and LV networks, the behavior is very similar, being somewhat higher percentages of variation of losses for LV to MV. For the MV network losses decrease to 18.4%, to a level of 40% adoption of randomly concentration, and increase to 18.6% for 100% adoption of consumption. For the LV network, the minimum is reached is 22.2%, for the same level of adoption and degree of concentration, and the maximum is 23.5% when 100% of consumption is adopted.

### 3.2.3 Hourly losses

This section provides an analysis of time variation of losses for two working days of winter and summer similar to Murcia case. Because irradiation is similar for both cases, the results obtained are very similar; giving only a difference for winter weekday scenarios deferred consumption.

In Figures 46 to 51, the time variation of the losses shown in the HV, MV and LV in winter and summer for each geographical concentration level with instantaneous consumption case. The figures concluded that the losses are reduced in all scenarios, the reduction being somewhat higher in winter than in summer.

Regarding the degree of geographical concentration, HV networks practically have no influence, whereas for MV and LV networks is observed a slight influence, with a smaller reduction of greater losses is the degree of concentration. This effect is more important in summer than in winter, because of higher radiation available for the same installed photovoltaic power consumption.

In Figures 52 to 57, the same results are for deferred consumption case. As the influence of the degree of concentration is more important to Murcia network, although, in this case, only increase losses for MV and LV networks in extreme degrees of geographic concentration in summer.

Comparing the results for each scenario, instantaneous and deferred consumption, is showed that loss reduction is higher for instantaneous consumption scenarios and, in turn, increased losses are lower. The effect is similar to Murcia and has the same explanation as indicated in paragraph 3.1.3.

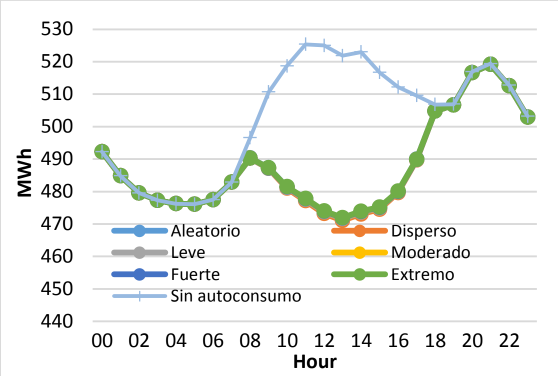



*Figure 46. Time variation of losses for HV Network, Madrid. 80% instantaneous consumption. Working day – Winter*

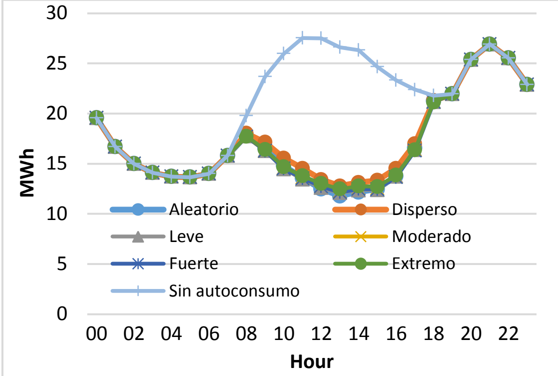



*Figure 48. Time variation of losses for MV Network, Madrid. 80% instantaneous consumption. Working day – Winter*

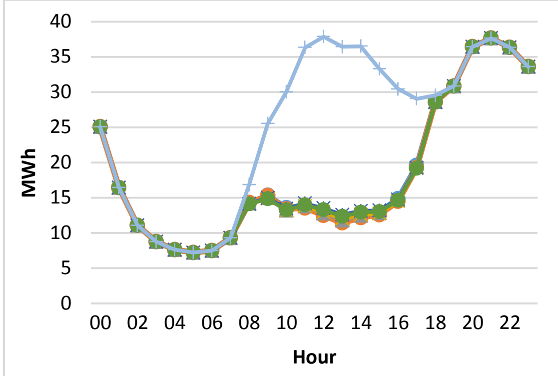



*Figure 50. Time variation of losses for LV Network, Madrid. 80% instantaneous consumption. Working day – Winter*

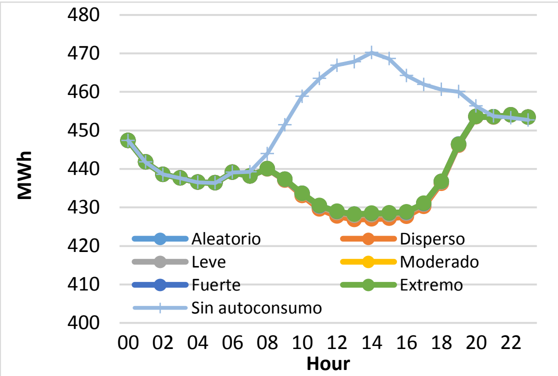



*Figure 47. Time variation of losses for HV Network, Madrid. 80% instantaneous consumption. Working day – Summer*

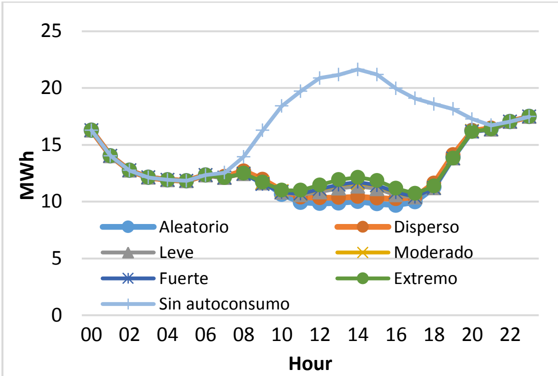



*Figure 49. Time variation of losses for MV Network, Madrid. 80% instantaneous consumption. Working day – Summer*

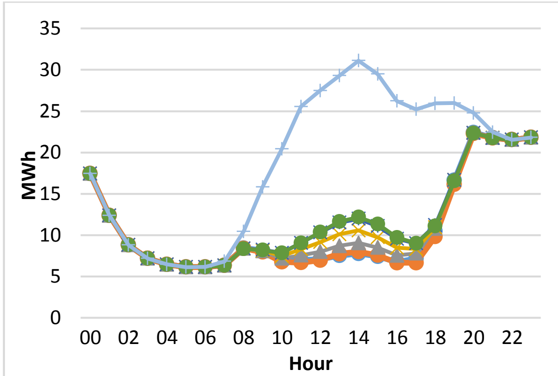



*Figure 51. Time variation of losses for LV Network, Madrid. 80% instantaneous consumption. Working day – Summer*

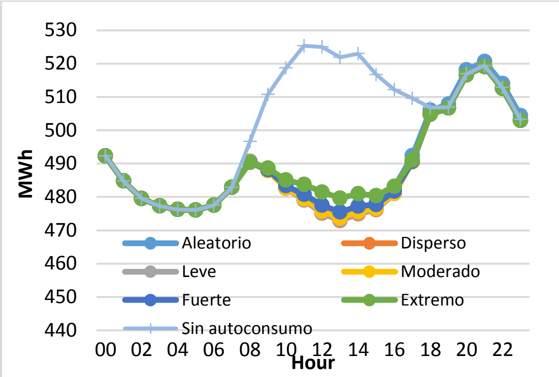



*Figure 52. Time variation of losses for HV Network, Madrid. 30% deferred consumption. Working day – Winter*

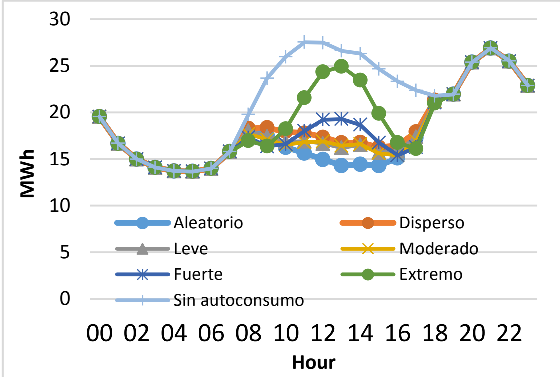



*Figure 54. Time variation of losses for MV Network, Madrid. 30% deferred consumption. Working day – Winter*

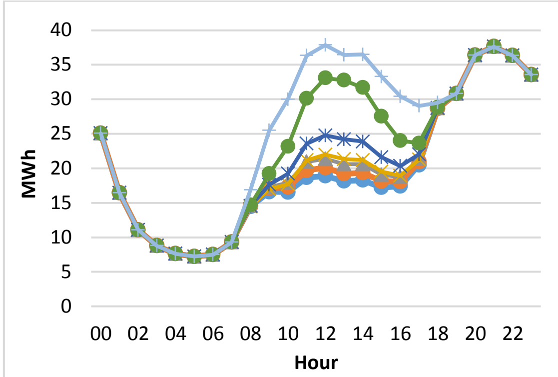



*Figure 56. Time variation of losses for LV Network, Madrid. 30% deferred consumption. Working day – Winter*

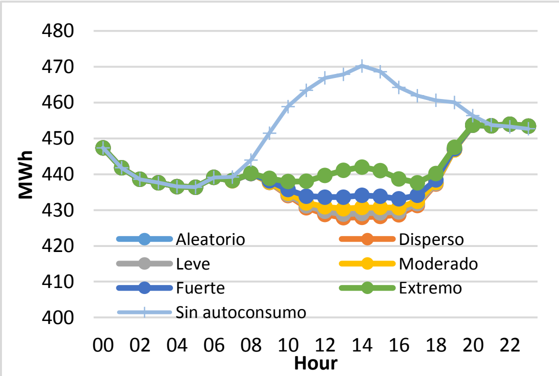



*Figure 53. Time variation of losses for HV Network, Madrid. 30% deferred consumption. Working day – Summer*

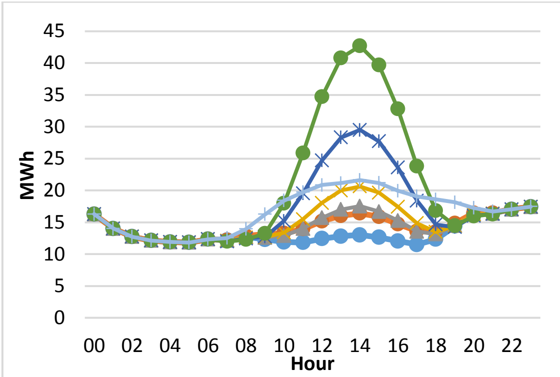



*Figure 55. Time variation of losses for MV Network, Madrid. 30% deferred consumption. Working day – Summer*

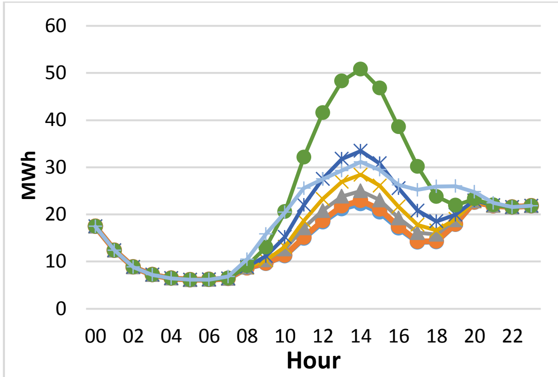



*Figure 57. Time variation of losses for LV Network, Madrid. 30% deferred consumption. Working day – Summer*

## 3.3 Network of Biscay

### 3.3.1 Photovoltaic generation

Table 11 shows the power consumption of PV installed in the MV and LV network of Biscay for each level of adoption and consumption scenario analyzed, along with the network peak demand in summer and winter.

Compared with the networks analyzed Murcia and Madrid, significant differences are observed in the relationship between installed PV capacity and peak demand. Thus, the installed photovoltaic generation exceeds the peak demand from adopting a level of self-consumption of 60%, for the scenario of instantaneous consumption, and 30% for the scenario of deferred consumption.

For a 100% adoption by consumption demand, the PV installed capacity would exceed by 93% the peak demand summer and 75% winter peak. In turn, for deferred consumption scenario, it would be 382% higher in summer and 337% higher in winter. These values are set by the lower irradiance available Biscay, implying that greater number of photovoltaic panels is required for the same level of self-consumption annual demand.

This effect is also apparent in the relationship between the average power output and the power installed, as shown in Figures 58 and 59. Thus, while in Murcia and Madrid practically takes advantage on peak of average irradiation summer 100% of the installed capacity in Biscay only 61% for a sizing for deferred consumption and 65% for sizing is used for instantaneous consumption.

| Adoption Level | Installed capacity PV (MWp) | | Peak Demand (MW) | |
|---|---|---|---|---|
| | Instantaneous consumption | Deferred consumption | Summer | Instantaneous consumption |
| 10% | 82 | 203 | 425 | 468 |
| 20% | 164 | 410 | | |
| 30% | 246 | 615 | | |
| 40% | 328 | 821 | | |
| 50% | 410 | 1025 | | |
| 60% | 492 | 1230 | | |
| 70% | 574 | 1436 | | |
| 80% | 657 | 1640 | | |
| 90% | 739 | 1845 | | |
| 100% | 819 | 2047 | | |

Table 11. PV capacity installed of self-consumption. Biscay

As for Murcia and Madrid, there are no major differences between the spring and autumn, giving the maximum difference of the three cases between the maximum irradiation available in summer compared to winter. Thus, the maximum radiation in summer is 43% higher than winter for solar peak hour.

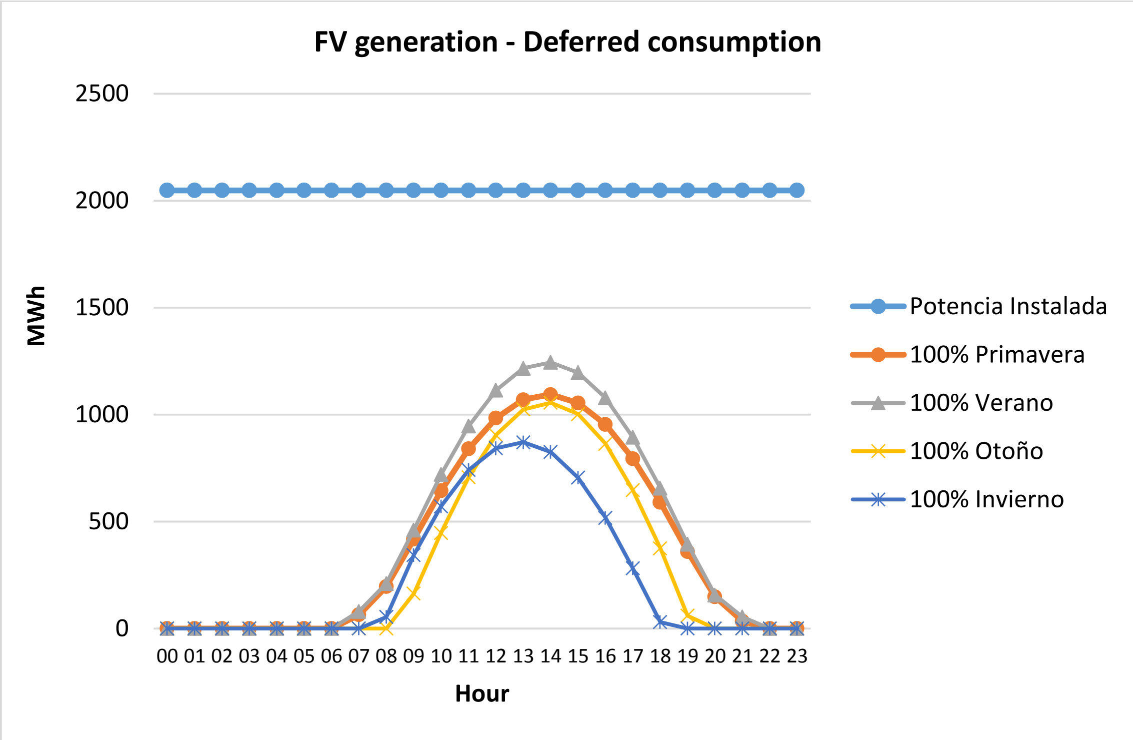



*Figure 58. Installed capacity and seasonal FV generation Biscay. 100% Deferred consumption*

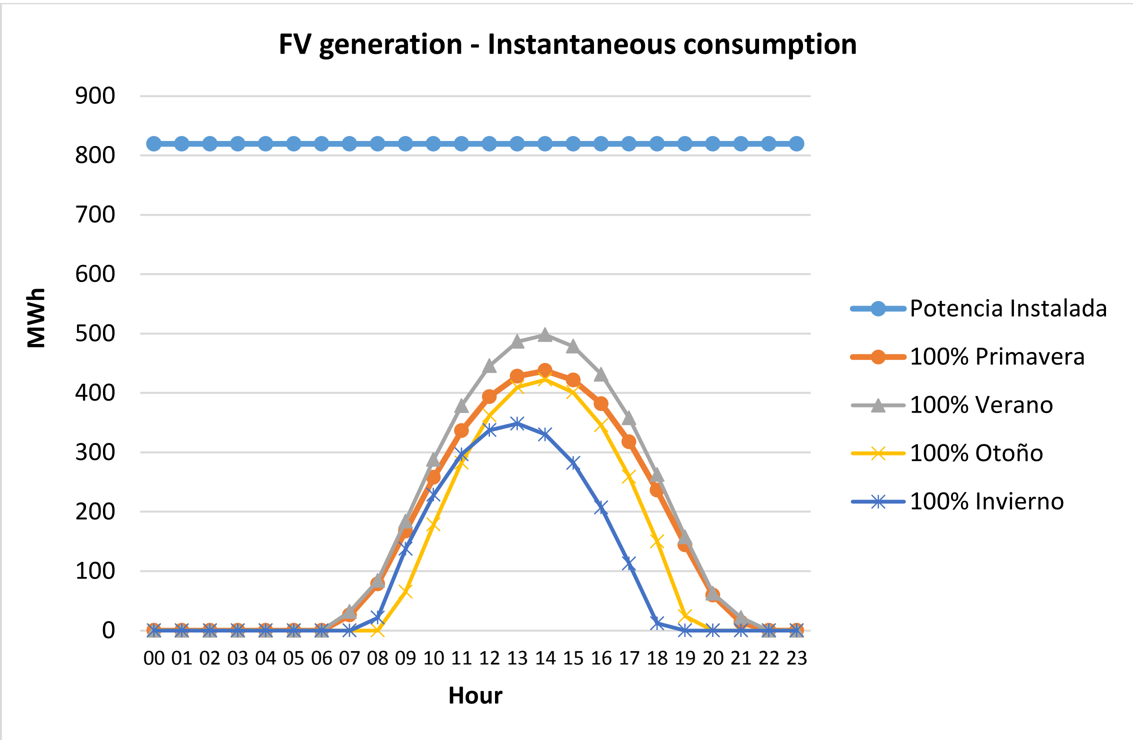



*Figura 59. Installed capacity and seasonal FV generation Biscay. 100% Instantaneous consumption*

### 3.3.2 Annual losses

In Figure 60 shown the variation of annual losses throughout the network Biscay (including variation in transmission network), regarding the case without consumption, for each level of adoption and degree of geographic concentration studied, when facilities consumption are sized for instantaneous consumption case.

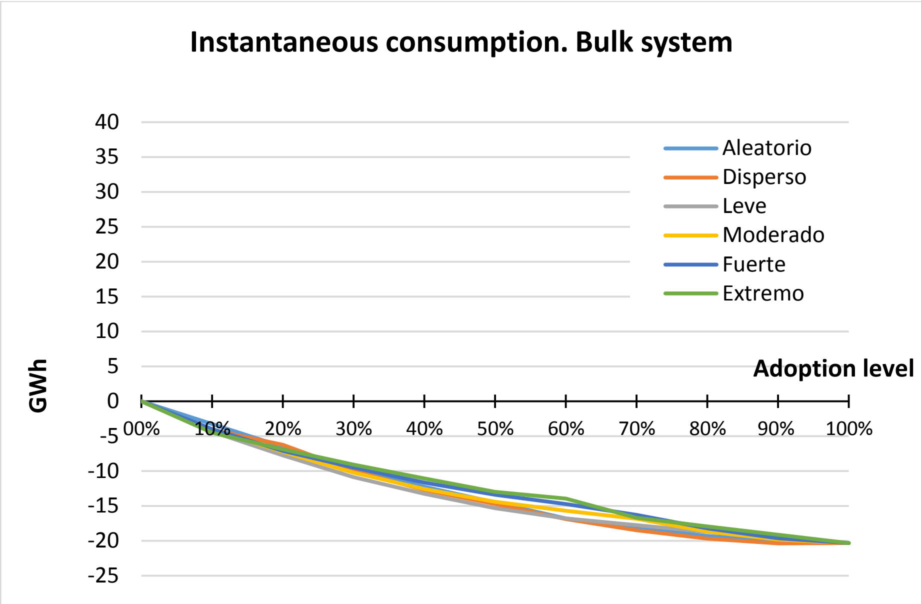



*Figure 60.* Total variation of losses of Biscay. *Instantaneous consumption*

As for networks of Murcia and Madrid, deferred MV and LV consumption reduces losses to all levels of adoption, reaching a maximum reduction of 20 GWh for 100% adoption.

When facilities of photovoltaic self-consumption are sized for the hypothesis of deferred consumption, similar to that observed for Murcia and Madrid behavior you are also obtained, although in this case, a smaller decrease in losses to low levels of adoption and a further increase is obtained when 100% adoption is reached.

Thus, as shown in Figure 61, the losses decrease between -3 GWh (10% adoption extreme degree) and -14 GWh (30% adoption random degree) to increase again to 36 GWh when reaching 100% adoption. Again, we observed that more concentrated photovoltaic consumption develops the greater negative impact on losses, the difference between the most favorable case (random) and the worst (extreme) the largest of the three networks analyzed. This is due to greater oversizing of photovoltaic panels in relation to the power demanded by the prosumers, caused by lower irradiation available.

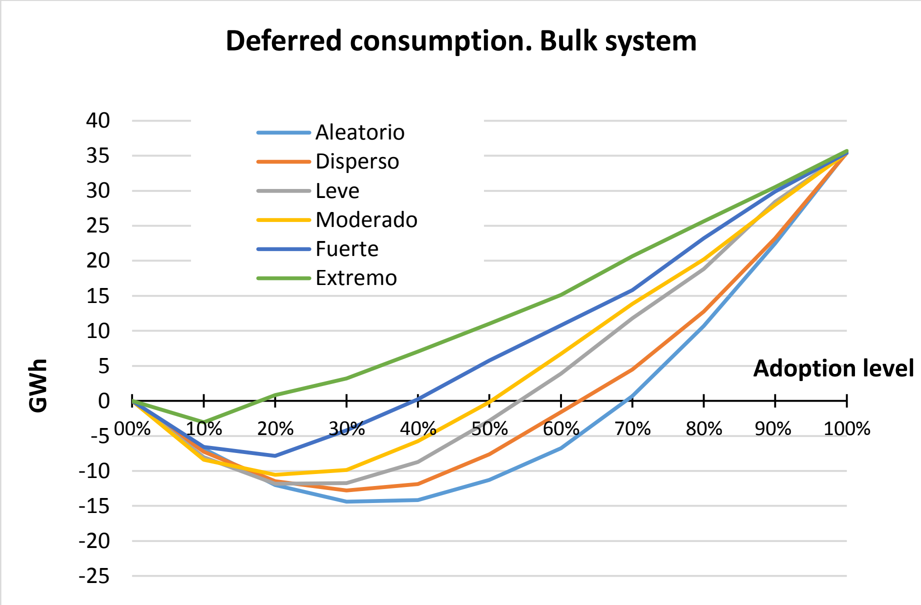



*Figure 61.* Total variation of losses of Biscay. *Deferred consumption*

In Figures 62 to 64 shown the percentage of change losses in Biscay, regarding the case without photovoltaic self-consumption, broken down by network-level, and with instantaneous consumption. You can see the same behavior as for networks of Murcia and Madrid, all the variation of losses occurs in the MV and LV networks.

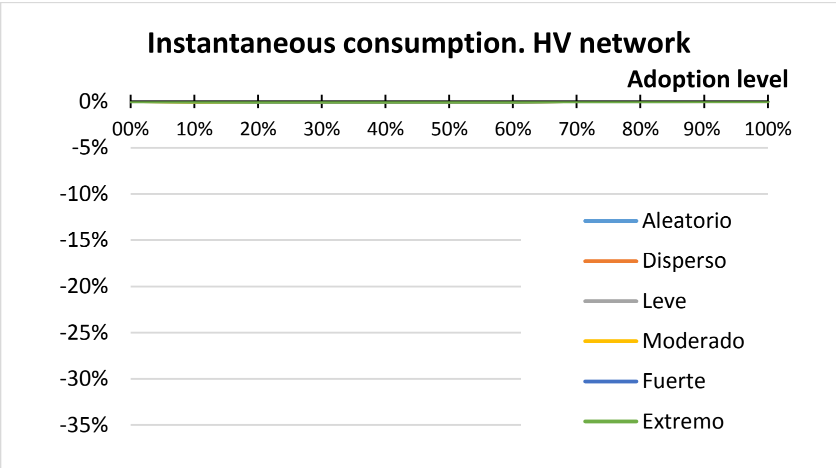



*Figure 62. Total variation of HV network losses in Biscay . Instantaneous consumption*

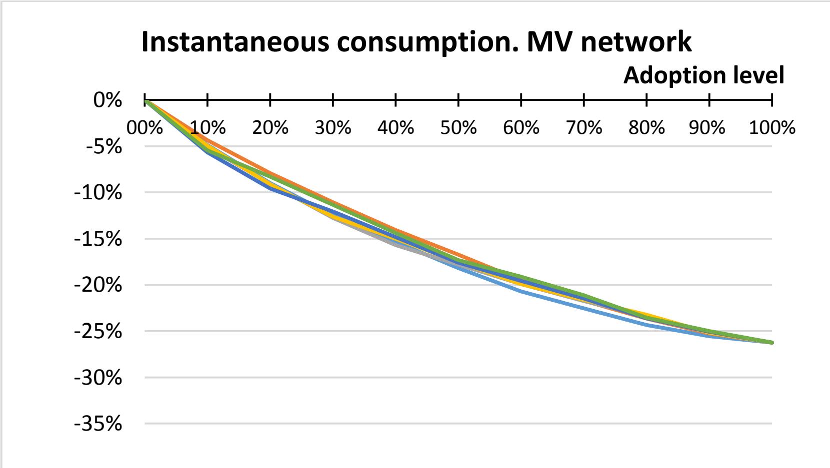



*Figure 63. Total variation of MV network losses in Biscay. Instantaneous consumption*

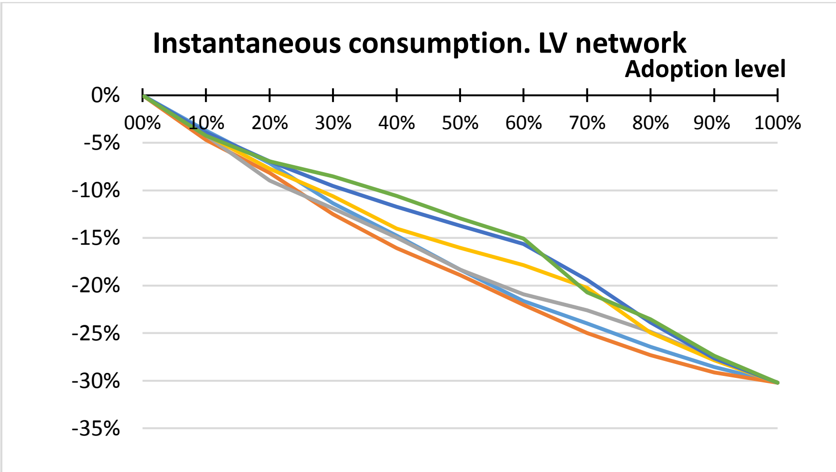



*Figure 64. Total variation of LV network losses in Biscay. Instantaneous consumption*

In the case of the Biscay network, the influence of instantaneous consumption on the HV is negligible. The reason is due to the low level of demand relative to that HV network. On one hand, the Biscay network is smaller than Murcia and Madrid; on the other hand, Biscay has two MV networks, 30 kV and 13.2 kV. The 13.2 kV network is powered by a LV transformer, while 30kV network primarily serves MV customers. In the MV model analyzed, only it took into account the 13.2 kV networks, while the network of 30 kV has been included in the model HV, as it serves as a link between the transmission network and the 13.2 kV distribution network.

For networks of MV and LV to increase adoption of FV self-consumption, losses decrease reaching a maximum decrease of 26% for MV network and 30% for LV network when all the demand of the distribution network has adopted consumption. In relation to the degree of geographic concentration of generation, seen as having more influence for intermediate LV adoption cases, being very small in the MV network.

In Figures 65 to 67 show the study results disaggregated by level network for deferred consumption hypothesis, with similar results of Murcia and Madrid. When photovoltaic self-consumption facilities are designed for a deferred consumption hypothesis for low adoption levels the losses are reduce to a minimum, from which point the losses increase again according to level of adoption.

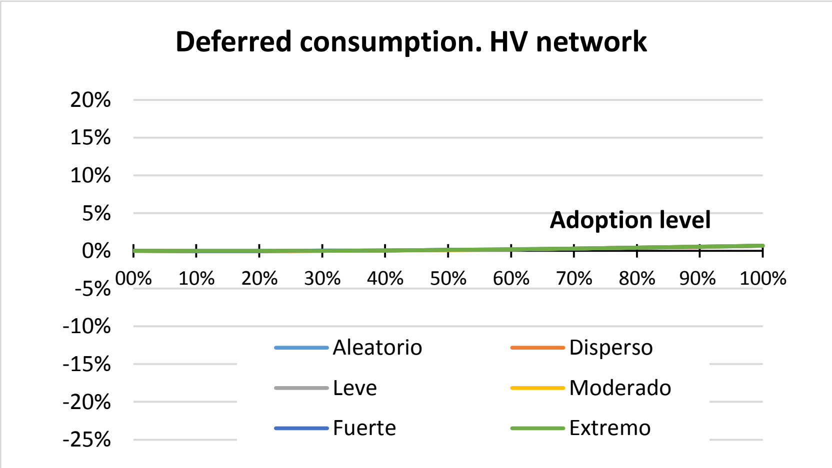



Figure 65. *Total variation of HV network losses in Biscay*. Deferred consumption

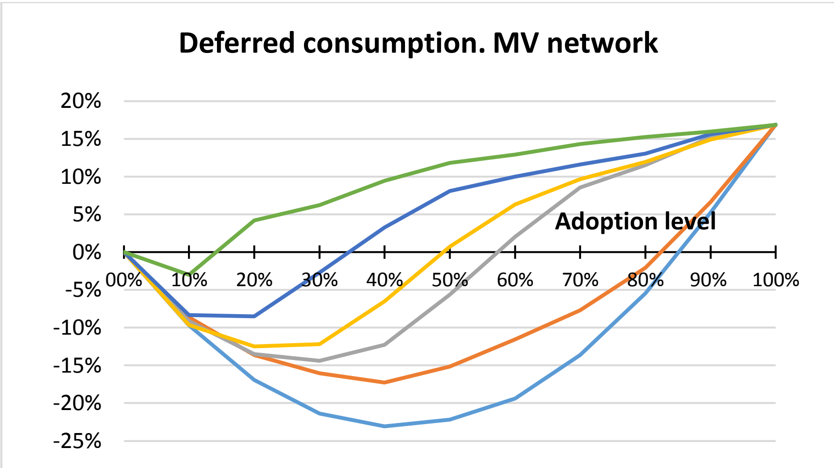



Figure 66. *Total variation of MV network losses in Biscay*. Deferred consumption

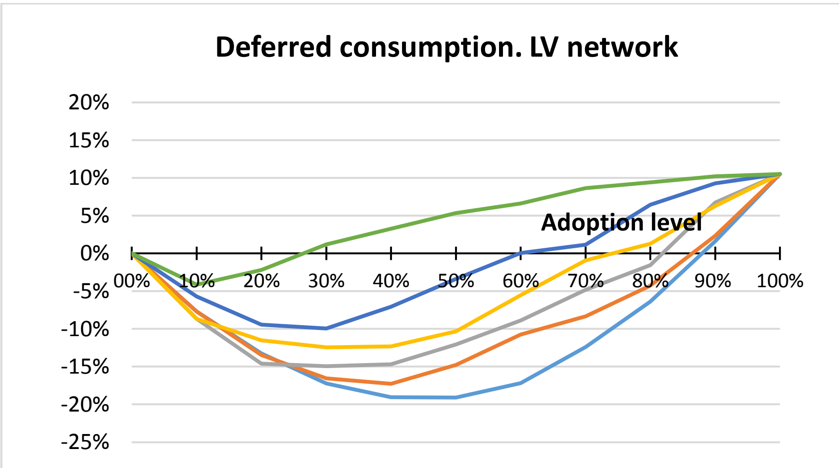



Figure 67. *Total variation of LV network losses in Biscay*. Deferred consumption

For the HV, practically no decrease losses, just one -0.01%, to increase above the stage without self-consumption, from a level of adoption of 30% up to a maximum of 0.67% for 100% adoption.

For MV and LV networks, the behavior is very similar, being somewhat higher percentages of variation of losses for MV to LV. For the MV network losses decreased to 23%, to a level of 40% adoption of randomly concentration, and increase up to 17% at 100% adoption of self-consumption. For the LV network, the minimum is reached at 19% at 50% adoption level with random concentration, and the maximum is 10.5% when 100% of consumption is adopted.

### 3.3.3 Hourly losses

In this section the same analysis for Madrid and Murcia of the time variation of losses for two working days of winter and summer. Due to the lower irradiation available in Biscay and the effect it has on the sizing of photovoltaic panels for consumption, greater variations between winter and summer not only for the case of deferred consumption, but also for instantaneous consumption case are observed.

The figures 68 to 73 show the time variation of the losses in the HV, MV and LV in winter and summer for each concentration stage when the option is adopted instantaneous consumption. It can be seen as the losses are reduced in all scenarios for medium and low voltage networks, while for HV networks increase in summer about the stage without self-consumption. In relation to the degree of concentration, influence is observed in MV and LV networks only for summer.

The figures 74 to 79 show the same results for the case of deferred consumption. Unlike networks Murcia and Madrid, the influence of the degree of concentration is important both in winter and summer. In winter, almost the same losses are obtained at time of maximum radiation for the three network levels when the degree of concentration is high. In summer, this effect is enhanced by the increased irradiation available, widely surpassing the losses on the case without consumption.

Finally, when compared to each other the results for instantaneous and deferred consumption scenarios, the same effect as reducing losses is greater for scenarios instantaneous consumption and in turn for networks of Murcia and Madrid, is observed, the increased loss is smaller.

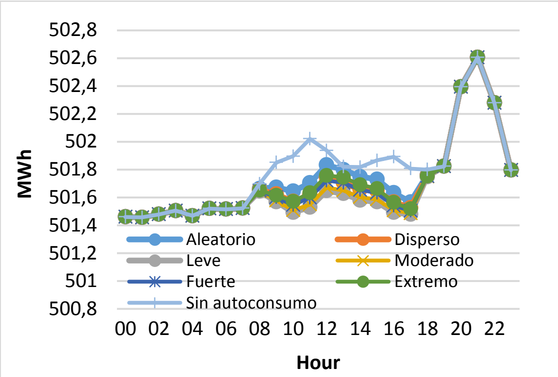



*Figure 68. Time variation of losses for HV network, Biscay. 80% instantaneous consumption. Working day - Winter*

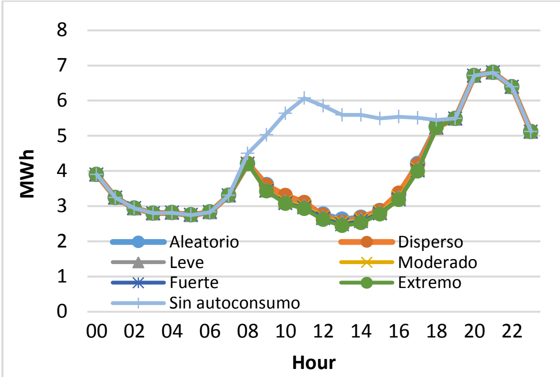



*Figure 70. Time variation of losses for MV network, Biscay. 80% instantaneous consumption. Working day - Winter*

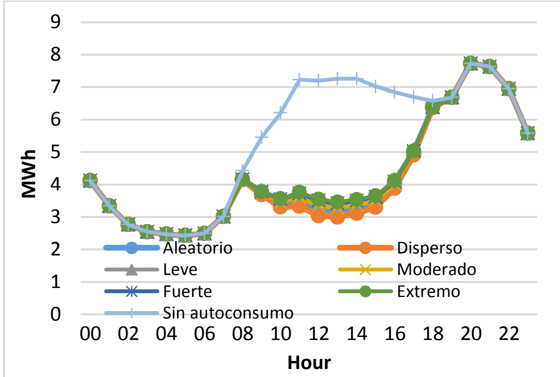



*Figure 72. Time variation of losses for LV network, Biscay. 80% instantaneous consumption. Working day - Winter*

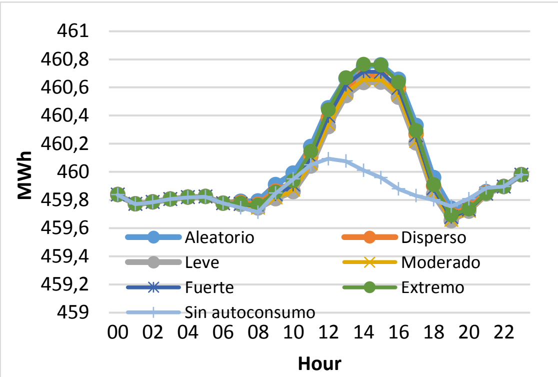



*Figure 69. Time variation of losses for HV network, Biscay. 80% instantaneous consumption. Working day - Summer*

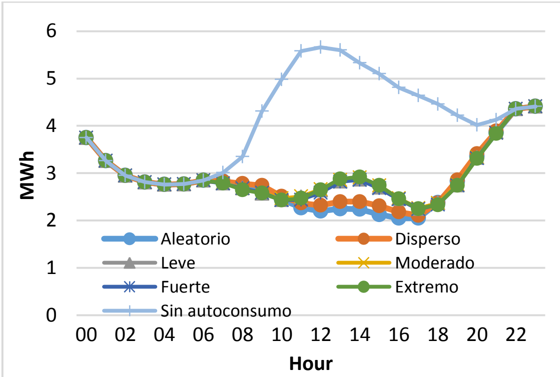



*Figure 71. Time variation of losses for MV network, Biscay. 80% instantaneous consumption. Working day - Summer*

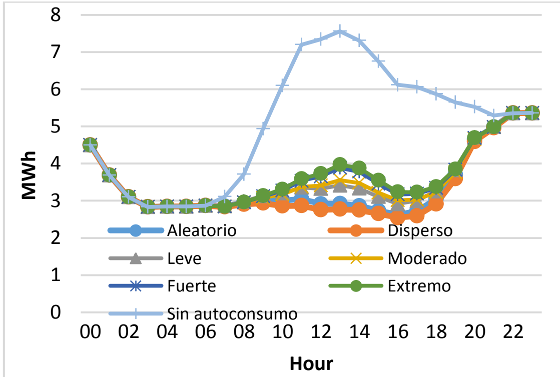



*Figure 73. Time variation of losses for LV network, Biscay. 80% instantaneous consumption. Working day - Summer*

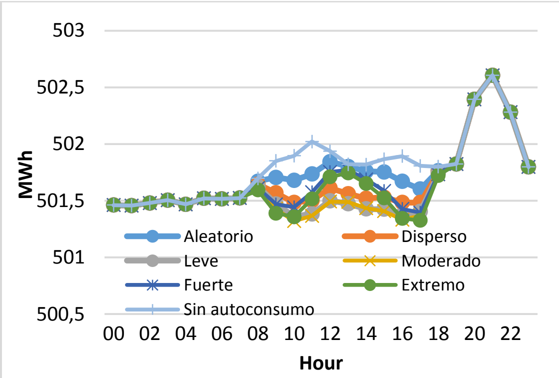



*Figure 74. Time variation of losses for HV Network, Biscay. 30% deferred consumption. Working-day - Winter*

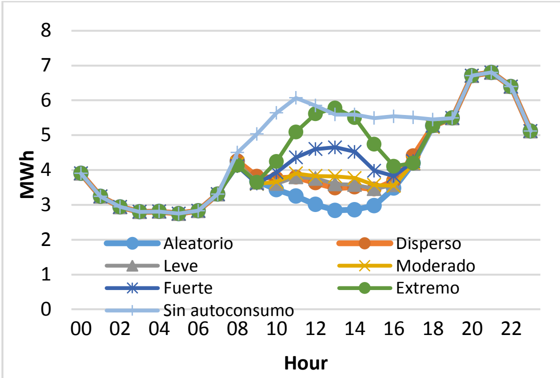



*Figure 76. Time variation of losses for MV Network, Biscay. 30% deferred consumption. Working-day - Winter*

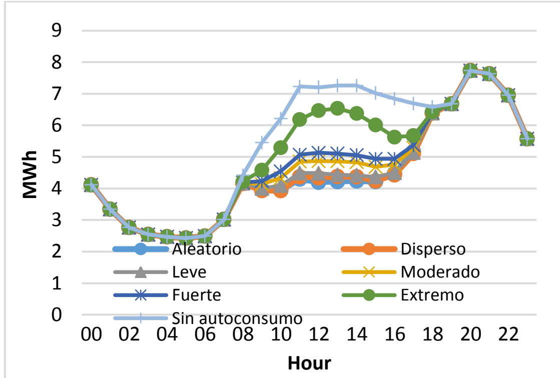



*Figure 78. Time variation of losses for LV Network, Biscay. 30% deferred consumption. Working-day - Winter*

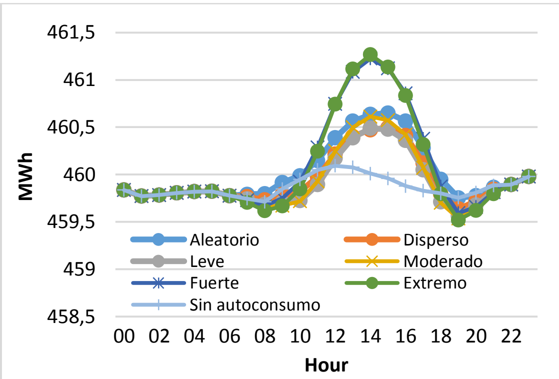



*Figure 75. Time variation of losses for HV Network, Biscay. 30% deferred consumption. Working-day - Summer*

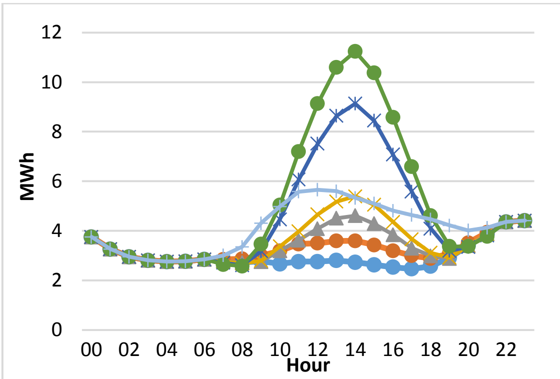



*Figure 77. Time variation of losses for MV Network, Biscay. 30% deferred consumption. Working-day - Summer*

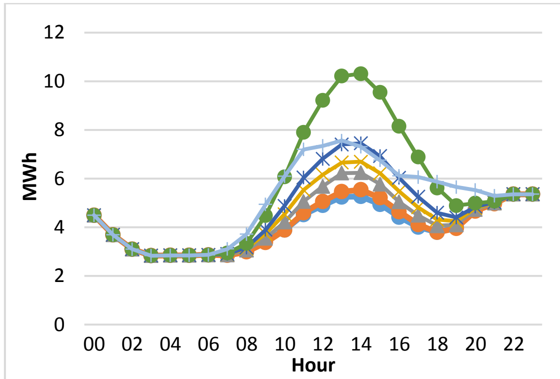



*Figure 79. Time variation of losses for LV Network, Biscay. 30% deferred consumption. Working-day - Summer*

## 3.4 Comparative analysis. Efficiency of generation

In the previous sections we have shown the individual results for each of the three areas studied network and have indicated the similarities and main differences between the three.

The three cases are different in terms of network structure characteristics, the type of demand supplied and level, and the available irradiation. However, the same behavior variation of the losses by increasing adoption level of self-consumption is observed from the stage without self-consumption to the scenario in which all customers of MV and LV networks adopt this option.

When the photovoltaic generators are dimensioned for a scenario of instantaneous consumption, losses diminish across the network for all levels of adoption, being this decrease diminishing with increasing adoption of household consumption. Additionally, it has been observed that Concentrating photovoltaic generation more in some network areas and in other cases a small influence, manifested in a lower reduction of losses by increasing the degree of concentration for intermediate levels of adoption.

For sizing of photovoltaic generators according to a scenario of deferred consumption, greater influence on network losses is observed. Initially, increasing the level of adoption from the stage without self-consumption, reduce losses, albeit to a lesser value than for instantaneous consumption scenarios. In all cases a minimum value of losses to a level of consumption that varies between 30% and 40% depending on the area network (Murcia, Madrid and Biscay) is reached. From this level the losses begin to rise again, increasing the level of adoption, exceeding the value for the stage without self-consumption. When 100% adoption is achieved losses are, in all three cases, higher than those without their self-consumption. Additionally, the degree of concentration has much influence on the losses. The more focused you are self-consumption; reduction of losses is lower and is given for a lower level of adoption.

From the point of view of energy supplying source, the analyzed demand of the three networks MV and LV in this study some power that comes from the transmission network is replacing by the energy produced by photovoltaic systems associated with self-consumption customer connected in networks MV and LV. For instantaneous consumption scenarios, is being replaced up to 40% of annual demand, when all customers of the distribution network adopt consumption; while for scenarios deferred consumption, the research substitution level is 100% of annual demand.

Therefore, the fact those, for a given scenario, the losses are lower than for the scenario without self-consumption means that there is gain energy efficiency by replacing centralized generation, from the HV, to distributed generation, from the MV and LV facilities of self-consumption. Conversely, if the losses increase means otherwise replacing centralized generation distributed generation causes a loss of energy efficiency for the whole system.

Thus, we analyzed the efficiency replacing centralized generation by photovoltaic distributed generation, from consumption as the ratio between the variation of losses for each percentage increase in the level of adoption and the amount of energy replaced. Looking ahead to the comparison results, it should be noted that, for instantaneous consumption scenarios, for every 10% increase in the level of adoption is replaced by 4% of the demand to MV and LV, while for the scenarios deferred consumption 10% is replaced.

In Figures 80-85, the results of the average efficiency of the replacement for the six scenarios studied concentration for networks of Murcia, Madrid and Biscay. In the higher figures are collected the results for instantaneous consumption and lower figures show the deferred consumption case.

In the three networks is gained efficiency with low replacement centralized distributed generation. As you increase the level of adoption of self-consumption, the efficiency decreases until a value is reached, in the case of deferred consumption, from which point efficiency is lost if centralized distributed generation is replaced by distributed generation.

You can see how the efficiency gains are greater for the Murcia network than Madrid and Biscay ones, which are concentrated with a high density of demand power, while Murcia is an extensive network with lower density of demand. Thus, in the case of Murcia, if 10% of centralized generation by distributed generation is replaced, for without self-consumption scnerio, an efficiency gain of 7.4% is obtained. In comparison, for Biscay network, that gain would be only 2.4%. Increase an additional 10% replacement of generation it implies that the efficiency gain is reduced to 3% in Murcia and 0.7% in Biscay. For Biscay, an additional 10% substitution of generation causes a loss of efficiency, while for Murcia, the efficiency gain is reduced up to 0.8%. From this level of deferred consumption, any further increase causes a loss of efficiency that is growing.

Therefore, from an energy point of view, the replacement of photovoltaic initially low levels of consumption is efficient. By replacing the centralized generation by distributed generation, losses are reduced. However, the substitution on moderate and upper levels of photovoltaic self-consumption is not energy efficient, since by displacing generation connected to the transmission grid and distribution network are increasing losses across the whole network.

It is necessary to note that, when comparing the energy efficiency of a centralized solution distributed generation against another, not only have to account for the increase or decrease of losses, but also the very efficiency of power generation. So, if you replace centralized generation distributed leads to improved efficiency of around 10% due to lower losses, any option centralized generation that was 10% more efficient than the distributed, it would always be the most efficient solution for whole electrical system.

In this regard, studies like MIT [3] indicate that centralized photovoltaic generation (large plants connected to the transmission grid) is at least 30% more cost efficient than photovoltaic distributed generation. Therefore, considering only the efficiency of the system, the results obtained in this study in relation to the variation of losses suggests that even low levels of adoption of photovoltaic self-consumption, would be more efficient to place the photovoltaic generation centralized level distributed.

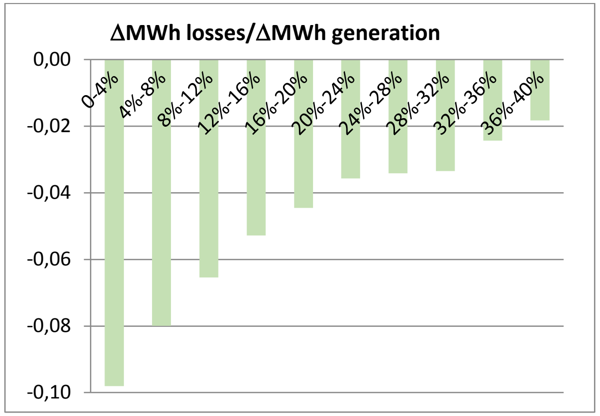



*Figure 80. Variation of total losses by the substitution of centralized generation by instantaneous consumption in Murcia*

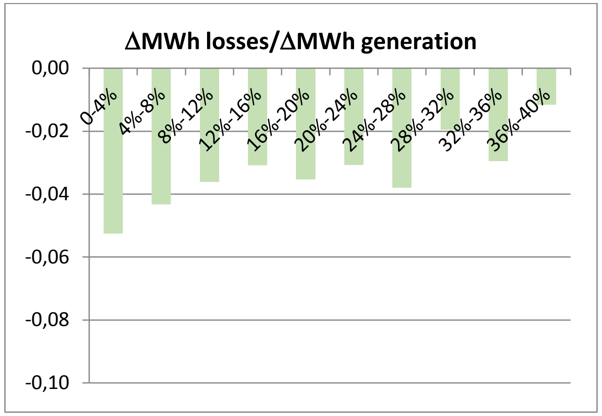



*Figure 82. Variation of total losses by the substitution of centralized generation by instantaneous consumption in Madrid*

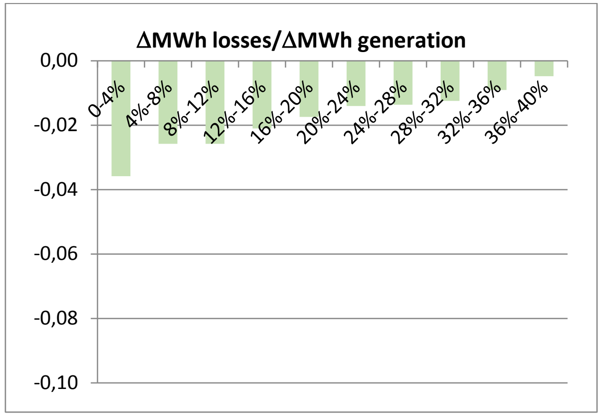



*Figure 84. Variation of total losses by the substitution of centralized generation by instantaneous consumption in Biscay*

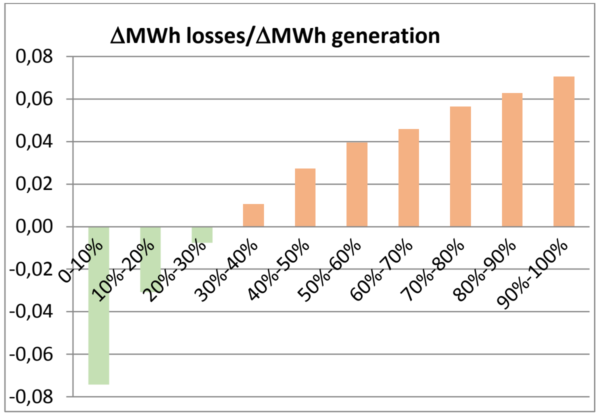



*Figure 81. Variation of total losses by the substitution of centralized generation by deferred consumption in Murcia*

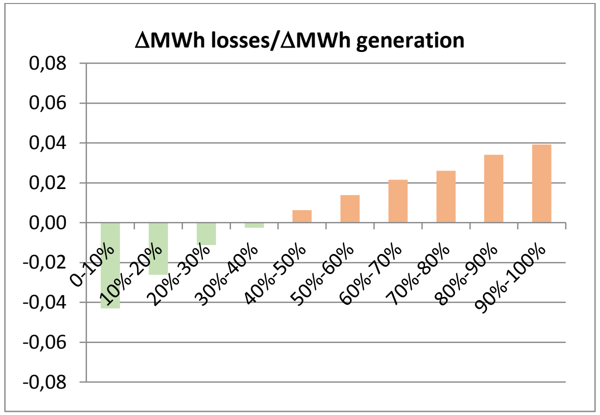



*Figure 83. Variation of total losses by the substitution of centralized generation by deferred consumption in Madrid*

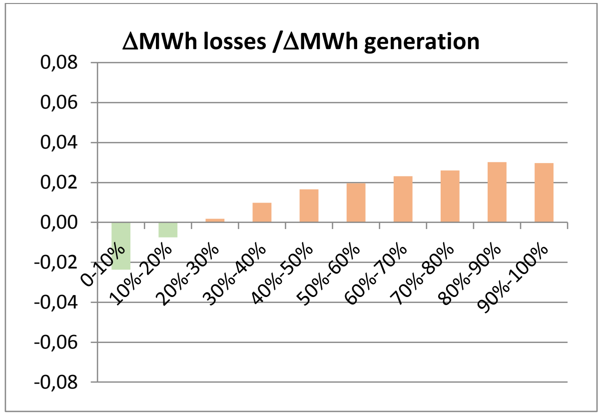



*Figure 85. Variation of total losses by the substitution of centralized generation by deferred consumption in Biscay*

The above analysis of efficiency has been made to the average of the six stages of geographic concentration, however, depending on what the degree of concentration of consumption in the network, the gains and losses of efficiency by varying losses in network are somewhat different in each case. In Figure 86 the efficiency in the case of deferred consumption in Murcia shown for each of the six stages of concentration.

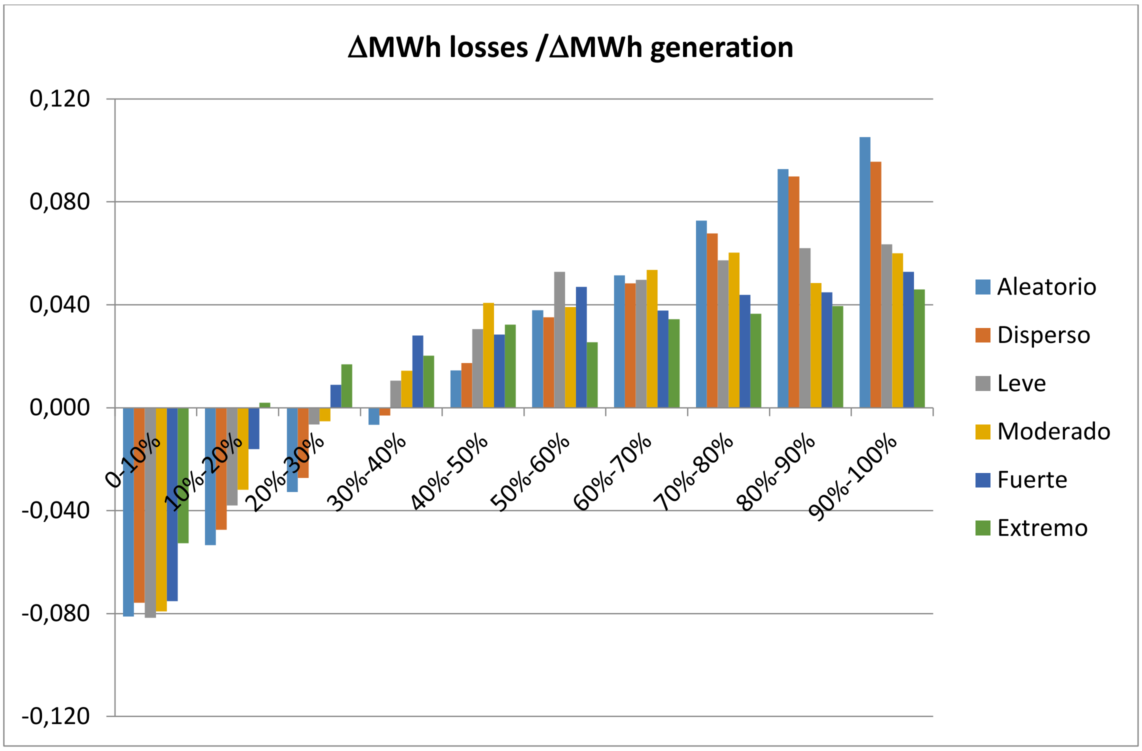



*Figure 86. Variation of total losses replacing centralized generation by distributed generation in Murcia depending on the degree of geographic concentration*

It can be seen how, for low levels of replacement of centralized distributed generation, efficiency gains is lower, the higher the degree of concentration of photovoltaic self-consumption. While for medium and high levels of substitution, the ratio is reversed, the greater the degree of concentration is lower efficiency loss. This apparent contradiction is a result of the methodology applied when designing merger cases. For low adoption levels of consumption, and the higher degrees of concentration, first self-consumption is installed in the network areas with lower load densities, which are those in which the losses increase to a greater extent, so the gain efficiency is lower. For making levels higher consumption, for grades higher concentration areas with lower load density already they have been saturated with facilities for self-consumption, which are available areas with great density load where rising losses is lower as well as the loss of efficiency.

# 4 Sensitivity to changes losses irradiation

The loss calculation methodology applied in GEDISPER uses the average hourly radiation of each month to which belong the eight days studied to model the photovoltaic generation facilities that produce consumption every hour. However, irradiation can take on hourly values depending greater or lesser degree of cloud cover, among other factors, so the same installed photovoltaic generation can produce more or less power.

Because of the nonlinear nature of the losses, which vary with the square of the current, the question is whether the increase in losses caused by increased export to the network when there is more radiation will be offset by the reduction in losses when the export is diminished as a result of lower irradiation.

Therefore, we analyzed the sensitivity of the calculation of losses to changes in the level of irradiation available with a dual purpose. The first results validate the losses calculated the average irradiation and, second, to study the effect produced on losses.

For the study it has not been able to count change values of the time irradiation for each month, but only with the values of variation of daily irradiation. These values are taken from the data base ADRASE [10] CIEMAT and presented as percentiles. This database gives, for each location, average daily irradiation, the 75 percentile and the 25 percentile for each of the 12 months of the year.

In Figures 87 to 89, the average daily solar radiation and percentiles 75 and 25 for three locations in Murcia, Madrid and Biscay is shown. It can be seen as irradiation is very similar to Murcia and Madrid, both mean values and for percentiles, whereas Biscay variations are much higher. Therefore, this analysis is presented only for networks of Murcia and Biscay.

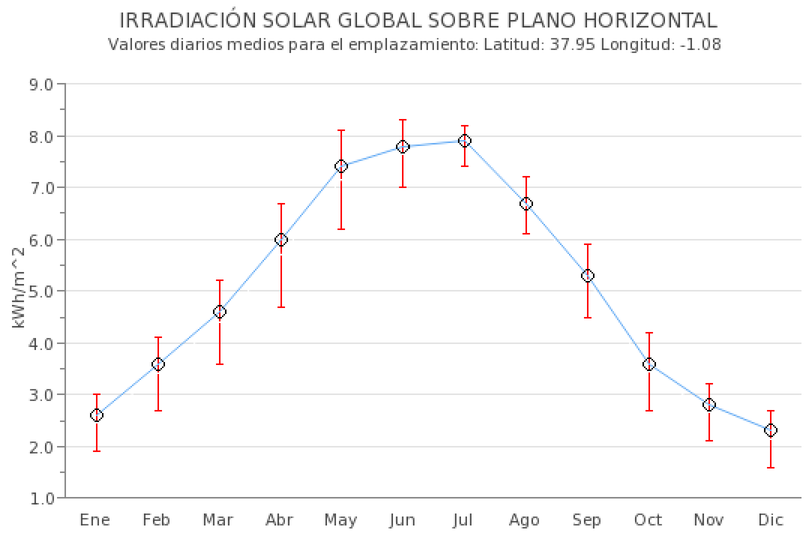



*Figure 87. Global monthly Irradiation in Murcia. Average and percentiles 75 and 25 values*

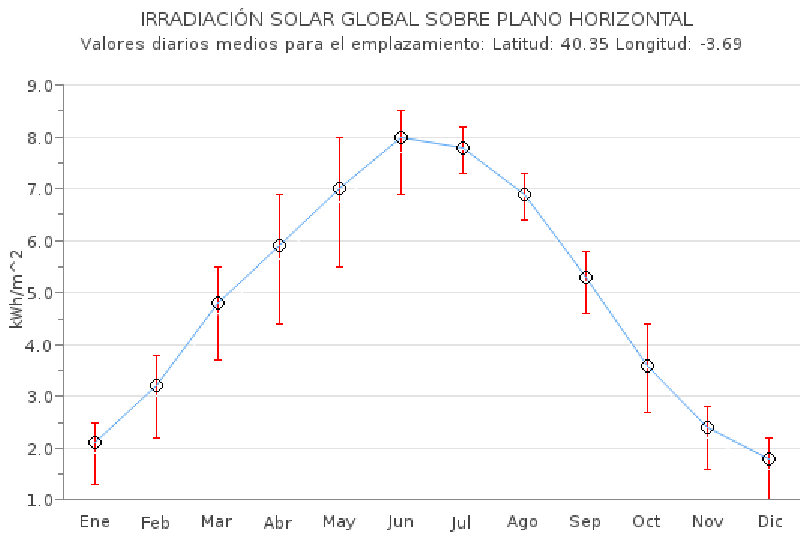



*Figure 88. Global monthly Irradiation in Madrid. Average and percentiles 75 and 25 values*

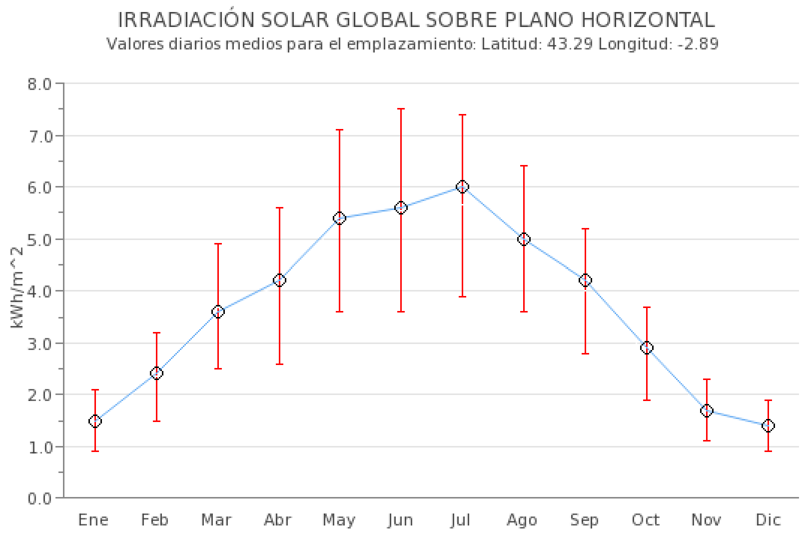



*Figure 89. Global monthly Irradiation in Biscay. Average and percentiles 75 and 25 values*

Because the loss calculation is performed for 24 hours, it is assumed that variations in hourly radiation follow the same relationship that the 75 and 25 percentiles compared to the daily average. Thus, it has been repeated for each network calculating losses the 132 scenarios for self-consumption, with an irradiation corresponding to the 25 percentile and the 75 percentile.

In Figures 90 to 101, results of the variation of total losses in the network of Murcia and Biscay to the 25 percentile, the average irradiation and percentile is 75. The above figures show the results for instantaneous consumption scenarios and lower for deferred consumption.

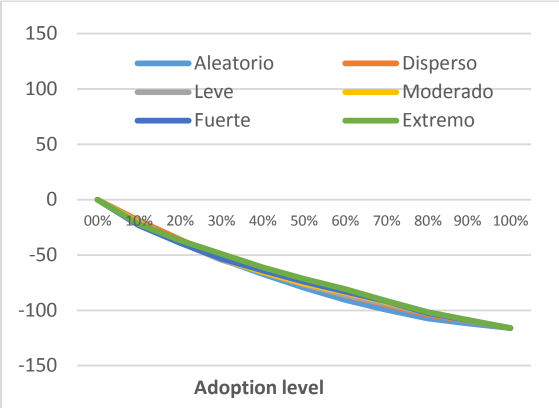



*Figure 90. Variation of losses in Murcia for instantaneous consumption. Percentile 25 solar irradiation*

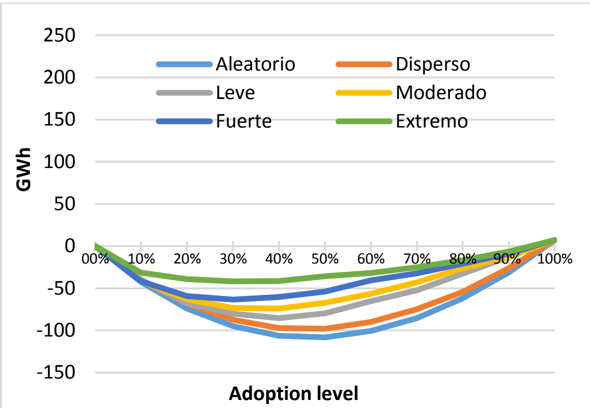



*Figure 91. Variation of losses in Murcia for deferred consumption. Percentile 25 solar irradiation*

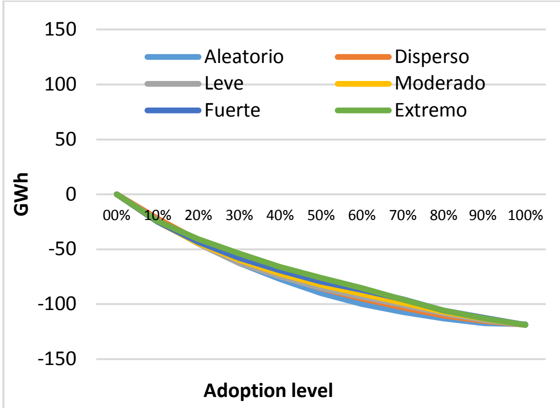



*Figure 92. Variation of losses in Murcia for instantaneous consumption. Daily average solar irradiation*

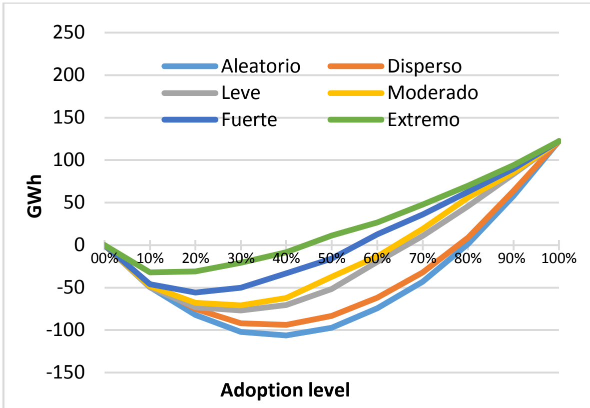



*Figure 93. Variation of losses in Murcia for deferred consumption. Daily average solar irradiation*

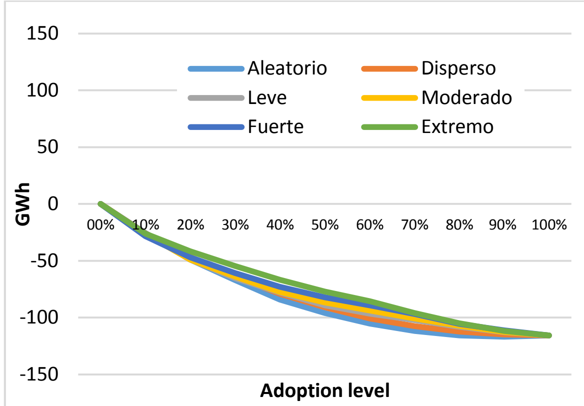



*Figure 94. Variation of losses in Murcia for instantaneous consumption. Percentile 75 solar irradiation*

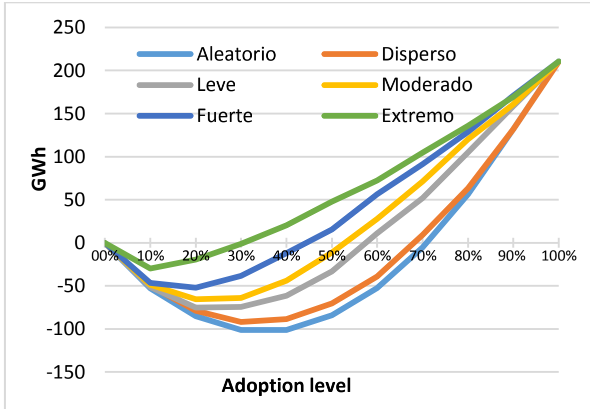



*Figure 95. Variation of losses in Murcia for deferred consumption. Percentile 75 solar irradiation*

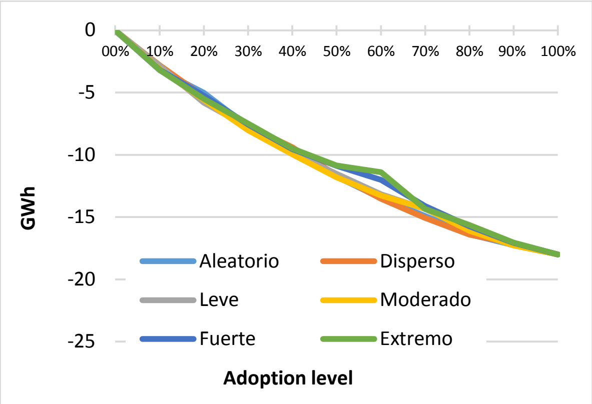



*Figure 96. Variation of losses in Biscay for instantaneous consumption. Percentile 25 solar irradiation*

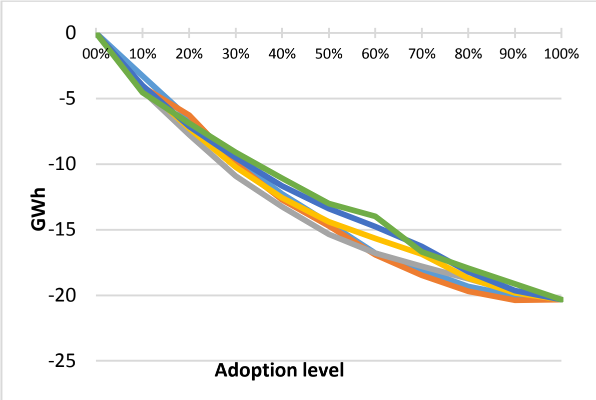



*Figure 98. Variation of losses in Biscay for instantaneous consumption. Daily average solar irradiation*

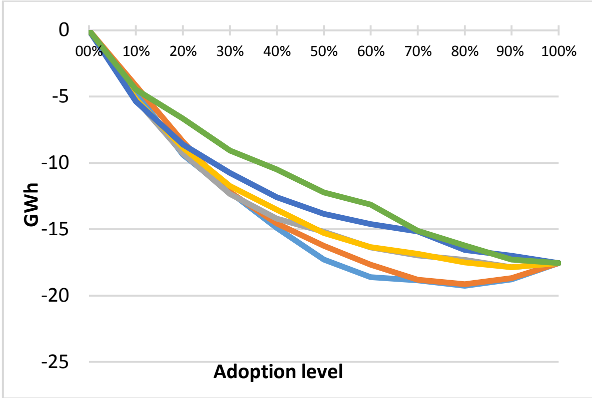



*Figure 100. Variation of losses in Biscay for instantaneous consumption. Percentile 75 solar irradiation*

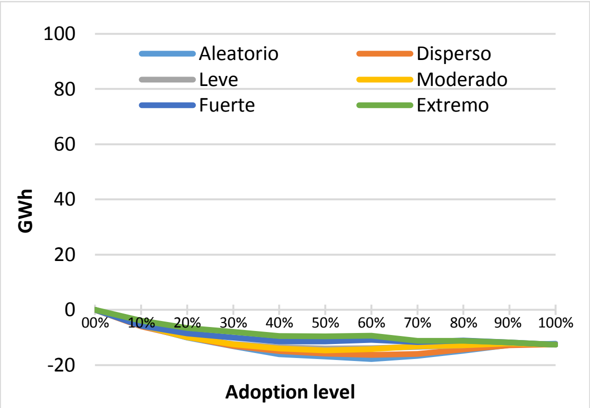



*Figure 97. Variation of losses in Biscay for deferred consumption. Percentile 25 solar irradiation*

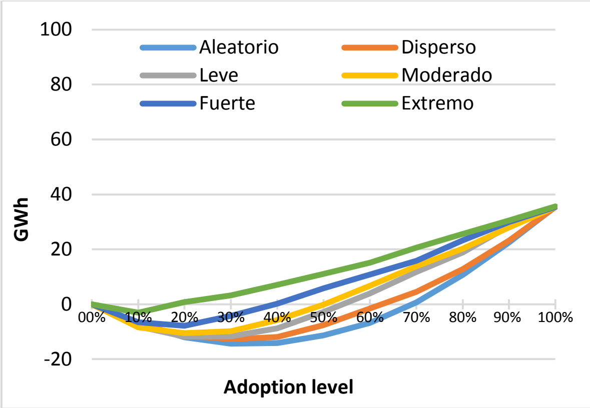



*Figure 99. Variation of losses in Biscay for deferred consumption. Daily average solar irradiation*

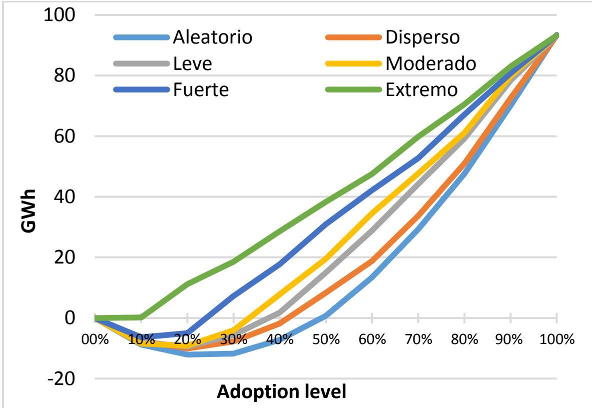



*Figure 101. Variation of losses in Biscay for deferred consumption. Percentile 75 solar irradiation*

Once the results obtained with percentiles have been calculated total annual losses of each network using the following formula:

Annual losses losses = 0.3 * Percentile 75 + 0.4 * + 0.3 * Media losses losses Percentile 25

That is, it is assumed that 30% of the days of the year irradiation are in the 75 percentile, 40% of days the irradiation is average, and the other 30% irradiation is in the 25 percentile.

The results of this calculation are compared with losses estimated annual average irradiation only and determined the error of an estimate of losses against each other. The results show that in all cases, if the average irradiation is used to calculate the losses an error default, in the worst case scenario is not more than 0.19% is obtained.

Therefore, the calculation of the annual losses average values using only irradiation is valid and also on the side of safety, and being estimated less losses than will actually by varying irradiation.

In addition to validating the calculation methodology, this study allows to analyze the influence of irradiation on the losses. It can be seen how, for scenarios instantaneous consumption, variation of losses in Murcia is very little affected by variations in irradiation, whereas Biscay shows that, for the 75 percentile concentration levels start to have importance.

It can also be seen as the minimum level of variation in network losses of Murcia little is little affected by the variation of irradiation. The maximum reduction of losses irradiation in the 25 percentile is -116 GWh, 2.5% less than the average reduction for irradiation and irradiation in the 75 percentile is -117 GWh, 1.7% less reduction.

To Biscay, the variation of the minimum level is somewhat higher. With the 25 percentile maximum loss reduction obtained is -18 GWh, down 10% reduction while the 75 percentile, the maximum reduction is -19 GWh, 5% less than for the average irradiation.

Where important variations are observed is deferred consumption scenarios. For the network of Murcia, with levels of solar irradiation in the 25 percentile, losses only increase compared to the case without consumption for 100% level of adoption, whereas solar radiation in the 75 percentile, increase from the level of 30% up to 70% depending on the degree of concentration. For the network of Biscay, this effect is more pronounced. For the 25 percentile decrease losses at all levels of adoption, while for the 75 percentile, the losses increase from the level of 10% to 50% depending on the degree of concentration.

Thus, for adoption of 100% in Murcia losses increase just 7 GWh with a level of irradiation in the 25 percentile, down 94% from the value with the average irradiation, but reach 210 GWh with irradiation in the 75 percentile, this corresponds to a 72% increase over the average irradiation.

For Biscay, again, variations are superior. With an irradiation at the 25 percentile for adoption 100% losses decrease 13 GWh, 136% less than the value with the average irradiation, and reaches 93 GWh with irradiance in the 75 percentile, corresponding to a 158 % more than the average irradiation.

Therefore, it can be concluded from this study that when photovoltaic systems are sized according to a criterion of deferred consumption, variability of radiation has a very high influence on the increase in network losses, still much higher on days with higher irradiation available. This effect is more important in areas with lower radiation available, due to the effect of oversizing of photovoltaic panels indicated in previous sections.

# 5 Verification of reasonableness scenarios concentration

## 5.1 Metodology

The methodology developed for verifying the reasonableness of scenarios aims to compare a real example of development of photovoltaic generation concentration scenarios developed in this study. In 2016, the penetration of photovoltaic self-consumption in Spain is low compared to other countries where there has been a promotion of this kind of consumption. However, in the power grid of Castilla La Mancha it has been a high penetration of photovoltaic generation, not associated with consumption in the medium-voltage network (MV). Knowing the reality of implementation of these generation facilities, we intend to see which scenarios concentration (random, disperse, low, moderate, strong and extreme) of simulated in this study it is most closely approximate reality in Castilla La Mancha.

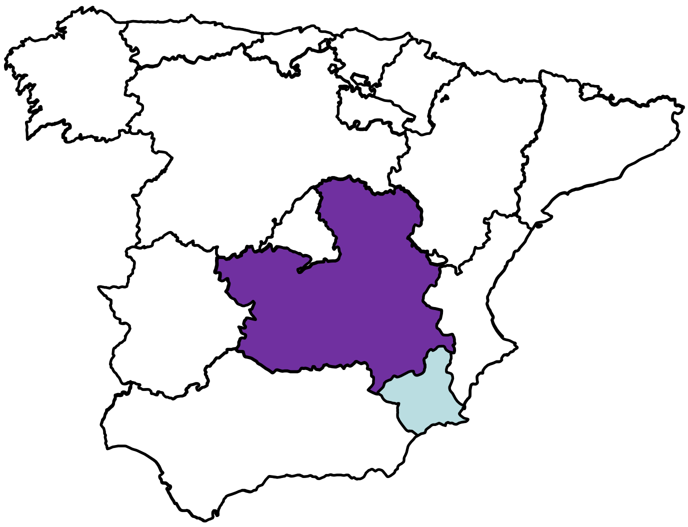


*Figure 102. Network Zones used in the verification study*

For comparison of the reality of concentration of generation in Castilla La Mancha with patterns used in this study, we have developed the following methodology:

1. Of all the scenarios of network simulation of Murcia are selected those that correspond to the level of actual adoption of photovoltaic Castilla La Mancha.

2. MV ordain sub-networks where photovoltaic power installed in groups of low to high density (D), calculated as the ratio of the annual burden of the subnet [MWh] between the total length of this [km].

3. Normalize the values of photovoltaic power installed for all groups in order to facilitate comparison.

4. We apply a formula of comparison to determine which of the six scenarios simulated concentration for the network of Murcia is closer to the reality of Castilla La Mancha. This formula is based on minimizing the square of the difference between generations normalized for each group.

$$Is = \sum_{i=1}^{n} (GD_{zc} - GD_{cs})^2 * i + \sum_{i=1}^{n} (GD_{zc} - GD_{cs})^2 * (n-i)$$

Where:

**Is** = index of similarity scenario cs

**i** = line or group of lines with a specific density.

**n**= total number of groups (20)

**GDzc**= Distributed Generation downtown area (Castilla la Mancha)

**GDcs**= Distributed Generation Case Study

Analyzed for each case study, the lowest index will match Is case study that most closely matches the reality experienced in the photovoltaic development in Castilla la Mancha.

If also the smallest of the indices Is obtained is sufficiently low, we conclude that the theoretical concentration scenarios used in this study may be representative of the realities of distributed photovoltaic generation growth in the future.

It is to decide if the rate is low enough, we establish a threshold corresponding to the index resulting from a difference between GDcz and GDCS 10% and equal for all groups.

In Figure 103 is displayed the diagram corresponding to the penetration of photovoltaic power bars (normalized with respect to one maximum value) for each of the groups density networks Castilla La Mancha.

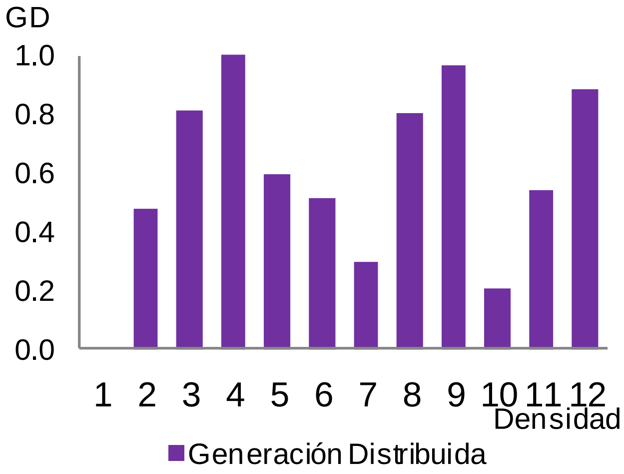



*Figure 103. Current Distributed Generation versus geographic concentration in Castilla La Mancha*

## 5.2 Results of Murcia verification

In Figure 104 we represent, also normalized per unit with respect to the maximum value, PV penetration levels for each group of density resulting from the scenarios studied in the previous chapters for the region of Murcia.

To facilitate comparison, we have taken 12 groups of density, which are available in the data of Castilla La Mancha.

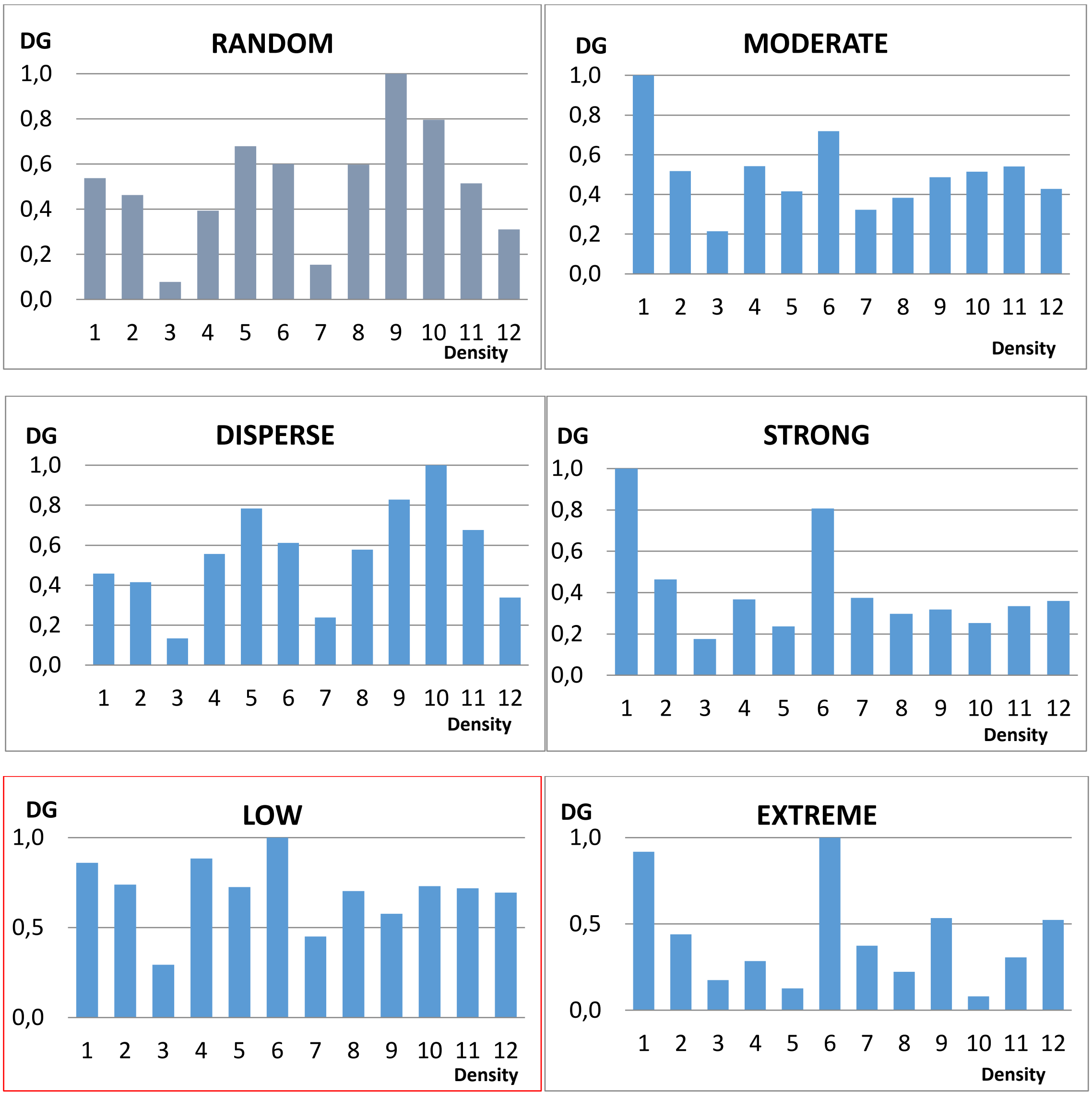



*Figure 104. Geographic concentration scenario for Murcia networks.*

For each level of concentration shown in Figure 104, is calculated the index Is resulting from the comparison of the data showed in Figure 103 of Castilla la Mancha. It is the smallest of the indices thus calculated, turns out to be for the "low" case.

Thus, the real growth of photovoltaic power in the region of Castilla La Mancha would correspond to the case called "low" in this study. It should be clarified that the photovoltaic generation of Castilla La Mancha is not associated with self-consumption and therefore its greater or lesser development is not conditioned by the demand in distribution networks.

However, the comparison methodology presented in this chapter will allow future actual developments associated adoption of photovoltaic self-consumption with more approximate level of concentration and infer in the behavior of network losses.

# 6 Other technical impacts

## 6.1 Voltage changes

The GEDISPER study focused on analyzing the influence of the energy losses with photovoltaic installations connected to network system. However, this is not the only technical influence that occurs on the network. Thus, the connection of distributed generation in a distribution network, changing power flows over the network, can cause overloads, modifying the levels of outages and voltage changes, as the most important conditions.

Both overloads as modifying outage levels are relevant to very high levels of distributed generation, however, voltage changes can be severe even for low levels of penetration of distributed generation.

When a generator is connected to the network is caused a variation in voltage at the connection point depends on the active power (P) and reactive (Q) injected by the generator and the resistance (R) and reactance (X) network at the connection point

$$\Delta V = P \cdot R + Q \cdot X$$

By injecting active power, a distributed generator causes an increase in the voltage will be greater the greater the active power injected and the greater the resistance network. This voltage rise can be compensated by the generator itself if capacity is available to absorb reactive power ($Q < 0$).

However, we must take into account the characteristics of the network where the generator is connected. Thus, MV and HV networks, networks are inductive, so that the resistance network is small relative to the reactance. However, LV networks are resistive networks, so that the resistance network is large related to reactance.

Therefore, the connection of generation transmission networks (HV) and medium voltage distribution networks (MV) cause a small increase in stress, which may be offset by the generator itself if it has capacity to regulate reactive power. On the contrary, the connection from generation to distribution networks of low voltage (LV) will cause a large increase in voltage, which is not possible to compensate for the generator, but is in command of your reactive power. This effect of increased voltage will be more important the more generation is connected in the network.

This study has considered that photovoltaic generators connected in MV and LV operate with power factor 1, that is, only inject active power distribution network reactive power being zero. This mode of operation is the most favorable for consumers, since it exploits the current capacity of the PV inverter to inject active power. In case you need also to inject reactive power, it would be necessary to have an investor with greater current capacity, thereby increasing the installation cost.

## 6.2 Voltage changes in Murcia network

For the 132 scenarios photovoltaic self-consumption analyzed for each network, in addition to calculating the value of losses, has determined the value of the voltage at all nodes of the network, to monitor when values are reached beyond the limits of operation network. Because the problem of surge depends on the amount of active power injected, it has been studied the most unfavorable case, which is the corresponding maximum when irradiation.

To illustrate the problem, in Figures 105 to 110 the voltage value of 98% of the nodes of the entire network, that is, the range of variation between percentiles 1% and 99% of all voltage values shown . The cases shown correspond to the peak time of irradiation for scenarios 30% level of adoption of instantaneous and deferred consumption, for a weekday winter (left figure) and another summer (right figure) and for each of six degrees of concentration studied.

In Figure 105 the range of variation of the stresses shown in all nodes of HV network with the operating limits of maximum and minimum voltage (red dotted lines). It can be seen as a level of 30% instantaneous consumption has no influence on the stresses of the transmission network. The values shown in Figure 106 indicate that either influence occurs when the consumption is delayed type.

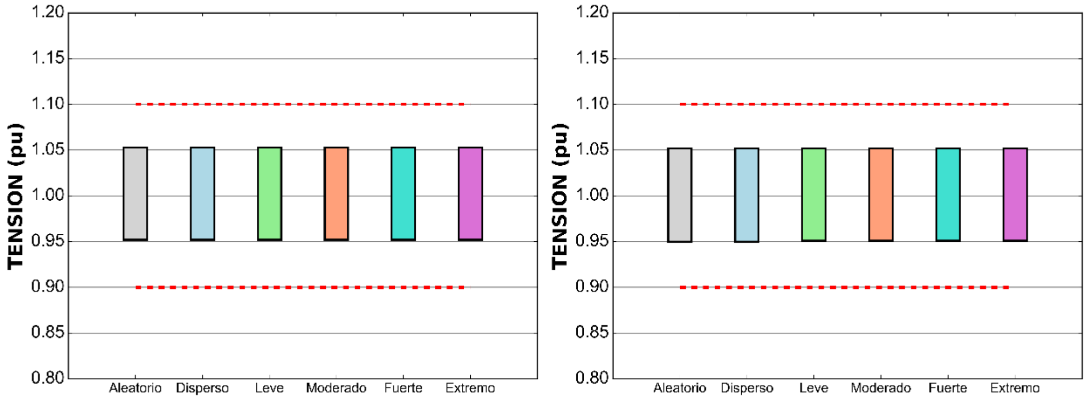



*Figure 105. Percentile 1% -99% of the HV networks voltages in Murcia on peak irradiation. Winter and summer working day. 30% instantaneous consumption*

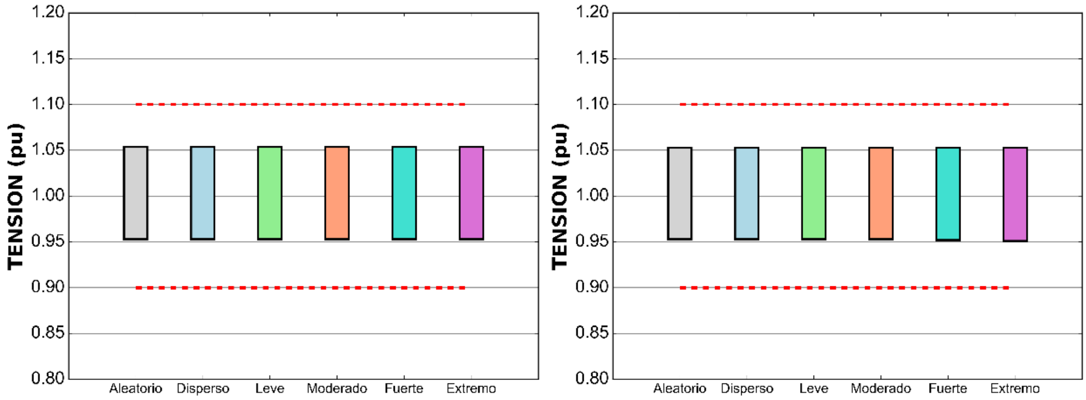



*Figure 106. Percentile 1% -99% of the HV networks voltages in Murcia on peak irradiation. Winter and summer working day. 30% deferred consumption*

The figures 107 and 108 show ranges voltage variation for the MV network. For instantaneous consumption (Figure 107), it shows that voltages tend to increase, although in all stages of concentration are kept within operational limits. However, for deferred consumption (Figure 108), adopting a level of only 30% and causes voltages go beyond the limits of operation from a moderate degree of concentration of consumption. This effect is more important in summer, being greater irradiation.

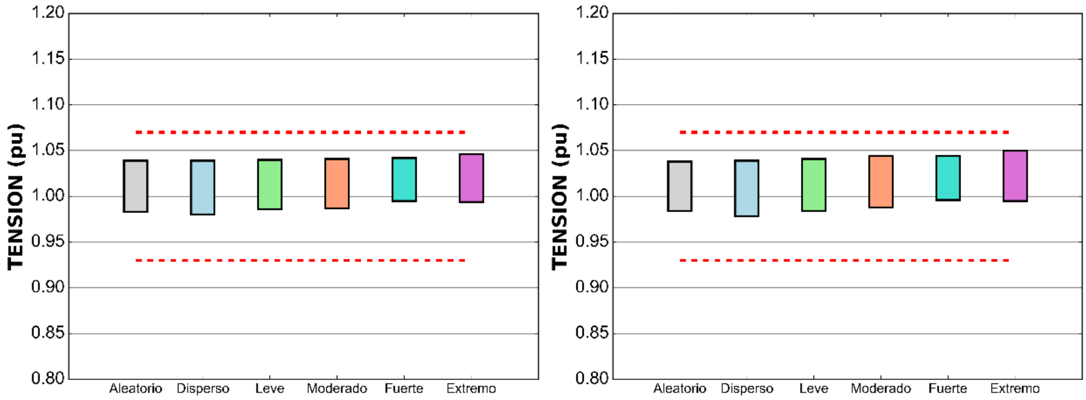



*Figure 107. Percentile 1% -99% of the MV networks voltages in Murcia on peak irradiation. Winter and summer working day. 30% instantaneous consumption*

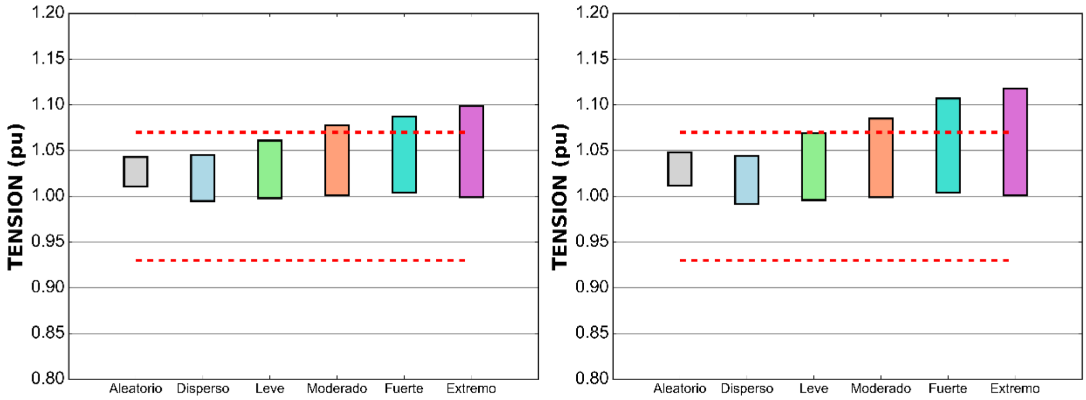



*Figure 108. Percentile 1% -99% of the MV networks voltages in Murcia on peak irradiation. Winter and summer working day. 30% deferred consumption*

Finally, Figures 109 and 110 analyze voltages in LV network. For instantaneous consumption (Figure 109), the voltages are within limits, although the range of variation is much higher than occurs in the medium voltage network. For deferred consumption (Figure 110), voltages are off limits in both summer and winter and low concentration scenarios.

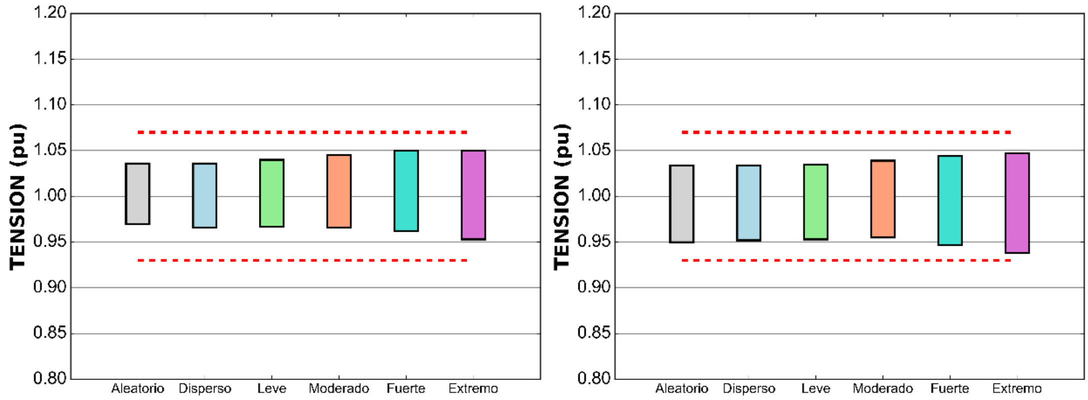



*Figure 109. Percentile 1% -99% of the LV networks voltages in Murcia on peak irradiation. Winter and summer working day. 30% instantaneous consumption*

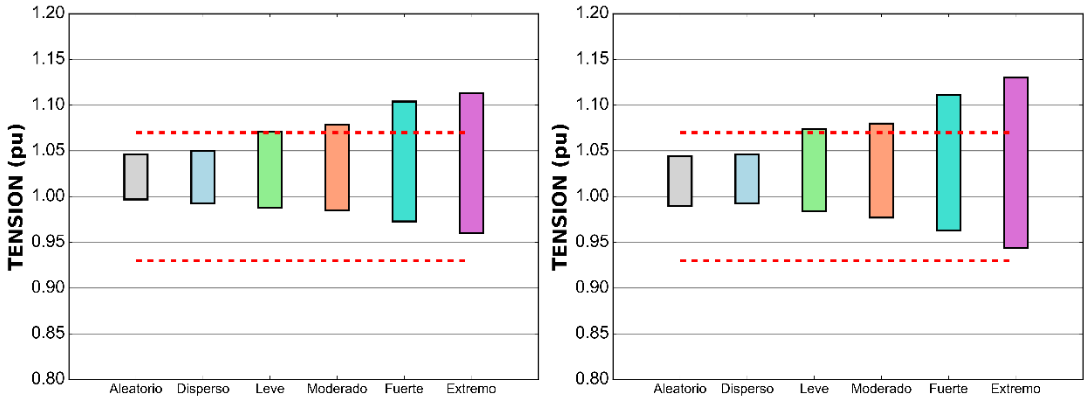



*Figure 110. Percentile 1% -99% of the LV networks voltages in Murcia on peak irradiation. Winter and summer working day. 30% deferred consumption*

The results shown indicate that, for low consumption levels of decision when it is developed under a deferred consumption sizing, voltage problems occur off-limits both the MV distribution network as LV. These problems occur not only in the summer but also in winter, although the available radiation is less.

By increasing levels of adoption of self-consumption problem is exacerbated voltages, even though consumption facilities be sized for the option of instantaneous consumption.

## 6.3 Measures available to reduce impacts

In the previous section has been revealed as the introduction of distributed generation associated with the consumption in the distribution network MV and LV surge causes problems even for relatively low levels of adoption self-consumption.

If you want to increase the penetration level of self-consumption in the network, it is necessary to implement measures to reduce the impact on voltages, so that the network is operating within regulatory limits. Such measures can be set, depending on the time horizon, both in planning and operation.

The measures available at the stage of network planning seek to prepare the network medium and long term to integrate a high level of consumption efficiently and safely, complying with the technical limits of network operation. Among these measures can include:

1. Increased capacity of the network elements. Increase the conductor cross section of the line with overloads, reduce brownouts allowed. The expansion of the power transformer substations that feed the network has the same effect.

2. New network topologies. Distribution networks MV and LV are radial current. The move to a ring or mesh topology allows operation with lower voltage variations at the expense of a much higher level of investment in both equipment and control devices and protection.

3. Installing new voltage control resources. The use of new resources for voltage control, over traditional based tap changers of transformers in substations and capacitor banks allow greater reserves of reactive power to absorb voltage variations. Among these resources can be cited:
    a. Line voltage regulators. They are transformers with on-load tap changer that are connected in series in the distribution lines surge problems. The load regulator can increase or reduce the voltage level of the entire line as necessary, depending on the particular operating situation.

    b. Reactance with voltage setpoint. It is reactances connected in banks bar MV of distribution substations and voltage controlled. Absorb reactive power chokes to limit voltage rise across the network.

    c. New MV/LV transformers with on-load tap changer. Currently transformers processing centers operate at a fixed voltage tap. The inclusion of a load tap changer allows varying the voltage across the LV network which limits voltage surges and allows for better integration of facilities subsistence.

4. Installation of new storage resources. The installation of storage systems would regulate power flows through the distribution network, so that overloads and surges, and allows more efficient management of energy is reduced. Storage devices can be centralized at the substation level, or distributed at the level of each individual facility consumption.

The measures available in operation consist of managing the network, control the means already available, in the most efficient way to ensure maximum penetration of consumption compatible with the limits of network security. Among these measures can include:

1. Office of the active power of PV generators. The problem of overvoltage is caused by the injection of active power, so control can help limit them. This control can be set:
    a. Based on slogans generation contract. The self-consumption must follow a generation program set in advance.

    b. Based on slogans of limitation. The self-consumption should limit or cancel the export of active network when power surges occur. While it is the most effective measure it is the least efficient, since it is a renewable resource wasting. Besides the economic impact caused by the self-consumption.

2. Reactive control of photovoltaic generators. PV inverters can vary their generation / reactive power consumption to help control voltage on the network. As noted above, this control is only effective on the MV network and requires an investment by the self-consumption, on a higher current capability together with a suitable control system.

In order to increase the level of adoption of photovoltaic self-consumption, or other forms of distributed generation within the distribution network MV and LV, you must implement many of the measures outlined above. All require increasing the investment, either in the distribution network, either in the self-consumption upgradeable, so they will have an economic impact in the form of higher rates or higher cost of network installation consumption.

## 6.4 Control voltage for the MV network Murcia

While it is not aim of this study to analyze the impact of voltage control strategies in network operation, the methodology developed allows include voltage control in the office of photovoltaic generators. Therefore, in order to analyze the effectiveness of this control and study its effect on network losses, has been studied for the network of Murcia the effect of the photovoltaic generators associated facilities consumption of customers MV network perform voltage control.

The study was conducted for the scenario of deferred consumption; since it is the more problems it generates surge low levels of adoption. They are sized photovoltaic generators for their self-consumption in MV capacity control with power factor 0.9 inductive to 0.9 capacitive to the rated active power. This requires that all investors are sized to power 11% higher than the peak power of the PV panels.

It has been used a strategy of distributed control and uncoordinated in which each investor tries to keep the stress in your node network connection to the MV in the nominal value (1 p.u.).

Applying the methodology developed calculation were determined losses across the network for each of the 66 scenarios deferred consumption and there have been voltages in all network nodes for all hours of the study.

comparison to the scenario-making level consumption of 30% of the variation of voltages in the MV network for solar rush hour working day winter shown in Figure 111, when no control is used voltage generators when MV and if used. Can be seen as voltage control is effective for all degrees of concentration of consumption. Voltages are within the operating limits and variation margin is narrower than when investors do not perform voltage control.

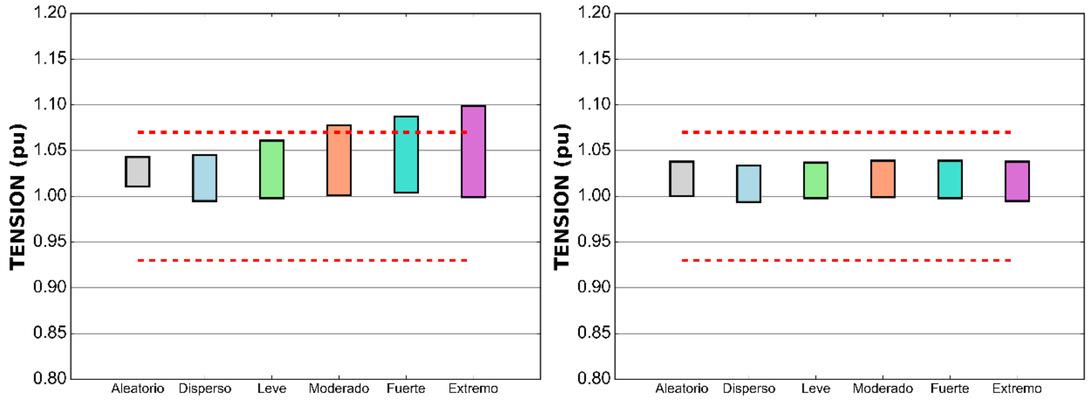



*Figure 111. Percentile 1% -99% of the MV networks voltages in Murcia on peak irradiation. Winter - working day. 30% instantaneous consumption. No Control Voltage (left) and with Voltage Control (right)*

In Figure 112 the results for a summer working days shows. It can be seen as variation margins voltages are somewhat larger but still controlled in the 6 scenarios studied concentration.

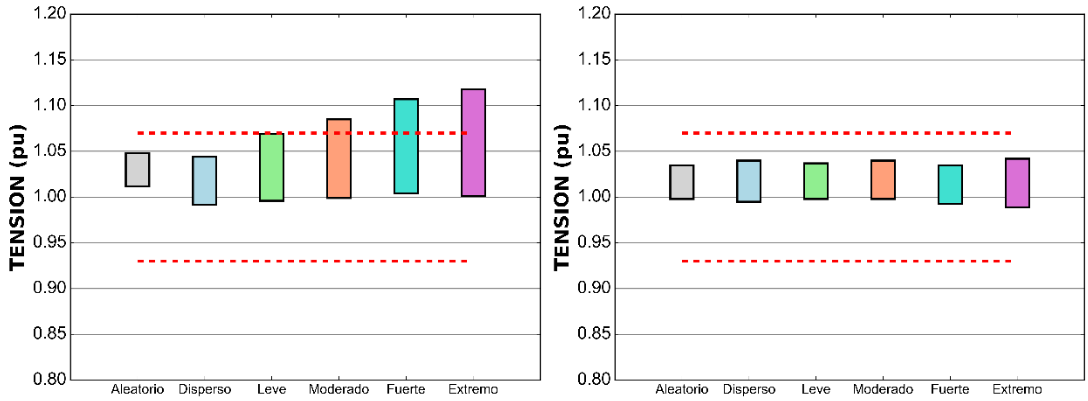



*Figure 112. Percentile 1% -99% of the MV networks voltages in Murcia on peak irradiation. Winter - working day. 30% deferred consumption. No Control Voltage (left) and with Voltage Control (right)*

It can be concluded, therefore, that the voltage control by the inverters connected to the MV network is a measure of effective operation to reduce power surges and operate the network within the voltage limits.

However, to reduce the overvoltages, investors must operate absorbing reactive power, which increases the current flowing through the network. This has a direct impact on losses, which increase for all scenarios studied on the case without control voltage, as shown in Figure 113. The maximum reduction of losses is reduced from -106 GWh to a level of adoption subsistence of 40% to -74 GWh to a level of adoption of consumption of 30%. Additionally, for the adoption level of 100%, the variation of losses increased from 122 GWh up to 253 GWh, 107% more.

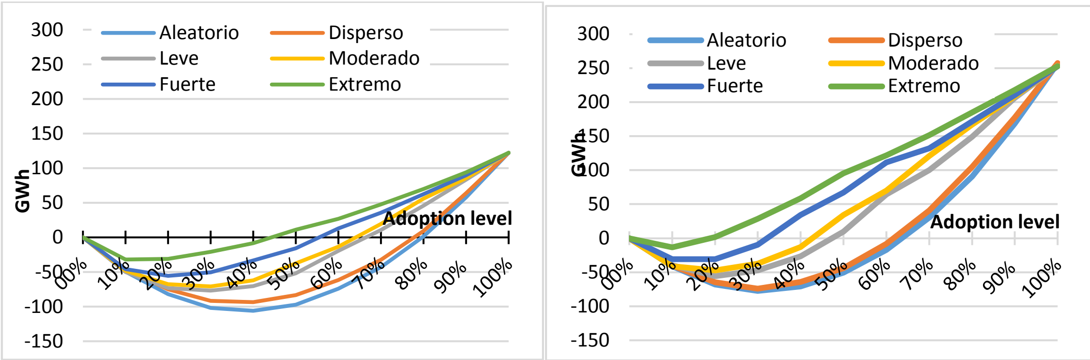



*Figure 113. Total variation of losses in Murcia. Deferred consumption. No Control Voltage (left) and with Voltage Control (right).*

The increased loss occurs not only in the MV network, as shown in Figure 114, but also in the transmission network that feeds it, Figure 115. The reason is that the reactive power are consuming investors MV is not available on that network, so it should be provided from the HV. This implies that the transmission network must have reserves of reactive power further to meet the demand of investors, with the consequent economic impact on both network operation and possible investments in resources reactive necessary to ensure that it has sufficient reserves.

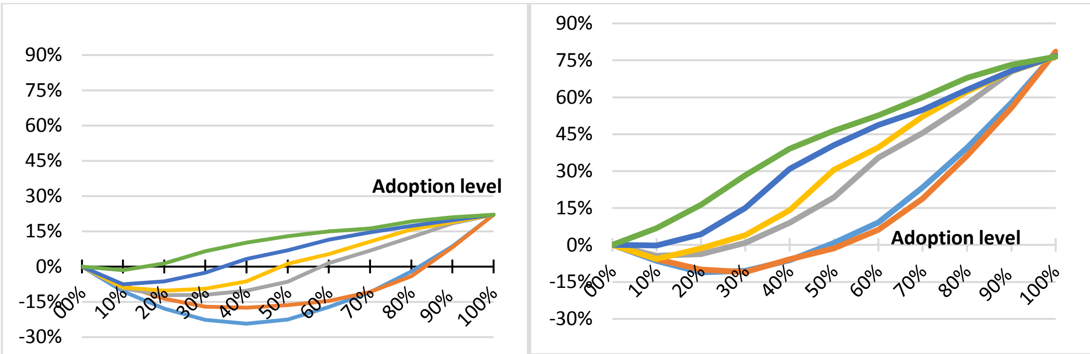



*Figure 114. Variation losses in MV networks, Murcia. Deferred consumption. No Control Voltage (left) and with Voltage Control (right).*

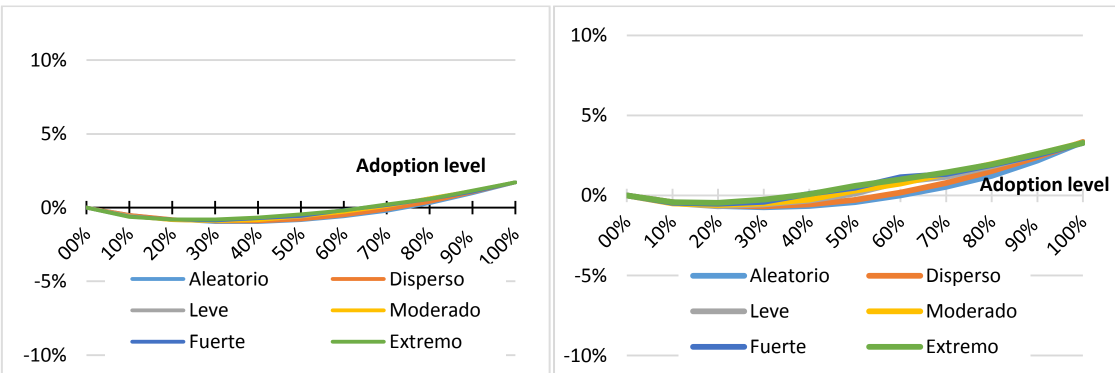



*Figure 115. Variation in losses in HV networks, Murcia. Deferred consumption. No Control Voltage (left) and Voltage Control (right).*

This study has shown that it is possible to limit surges in the MV network using capacity control voltage PV inverters, even at the expense of increasing the cost of network operation in the form of higher losses in both network MV distribution and transmission network, and in the form of increased use of resources control reactive transport. In addition, increased investment by self-consumption is necessary, to an investor need higher capacity and by network operators, having to ensure greater reserves of reactive power.

In short, the downside is a loss of energy efficiency for the entire system, as can be seen in Figure 116. By implementing the control voltage, gain efficiency by replacing centralized generation by distributed generation is reduced to low levels of consumption. In turn, the loss of efficiency increases for medium and high levels of adoption.

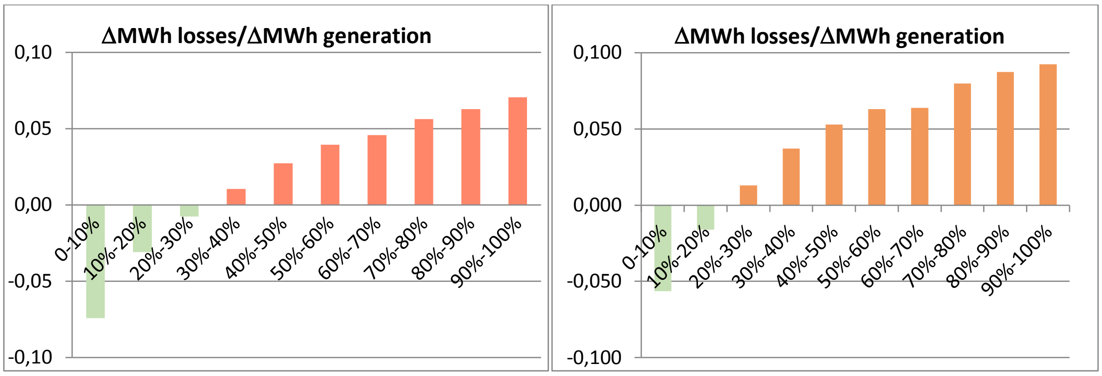



*Figure 116. Total variation of losses by the substitution of centralized generation with self-consumption in Murcia without MV Voltage Control (left) and with Voltage Control (right). Deffered consumption cases.*

# 7 Conclusions

The GEDISPER project is a research project carried out with the aim of discovering the true impact on network losses caused by the distributed generation associated with self-consumption of customers connected in networks of medium and low voltage. We carried out a detailed analysis with real data of transmission and distribution networks, using values of actual demand in the Spanish regions of Murcia, Madrid and Biscay in 2014.

The project presents scenarios of development of photovoltaic self-consumption by analyzing the most plausible regulatory schemes that would determine the degree of adoption and expected size of self-consumption installations. Also, different possibilities of development based on more or less geographical concentration of self-consumption facilities are analyzed, from a perfectly homogeneous development to a more concentrated development.

Power flows are calculated or each of those scenarios. Yearly losses have been determined across the network.

From the analysis of the results, it has been concluded that in regulatory frameworks that minimize the surplus of power exported to the grid, called Instantaneous consumption, the impact of distributed generation is clearly beneficial as far as losses are concerned. In the best cases, losses are reduced up to 30% in MV and 39% in LV. Additionally.

However, in regulatory frameworks that favor generation surpluses fed into the grid, as is the case in the so-called "Net Metering" arrangements, the results are mixed. They range from a reduction in losses of 24% in MV and 30% in LV, for moderate penetrations and homogeneous geographic development, up to increases in losses of 22% in MV and 23% in LV, corresponding to situations of high penetration of self-consumption very geographically concentrated.

The study has also found that the variation of losses occur at all network levels, although the highest percentage changes are observed in medium and low voltage networks. Additionally, it is in these networks where the influence of the geographic concentration is more significant.

Therefore, it cannot be stated categorically that PV self-consumption would always reduce network losses. On the contrary, incentive policies such as "Net Metering" can lead, not only to an increase in energy losses in the networks, but also induce the need of network reinforcements to keep the same quality of voltage.

The scenarios analyzed in this study gradually replace centralized generation with PV distributed generation. We can associate the reduction in losses with an energy efficiency gain. In low self-consumption adoption scenarios energy efficiency is gained in all network levels, namely LV, MV and HV. As adoption increases, the efficiency gain diminishes up to a point in which in some scenarios further adoption of self-generation turns out to produce negative efficiency, that is, increase in overall losses. It has been observed that efficiency gains are higher in Murcia than Madrid or Biscay, due to Murcia being a larger less loaded network.

Moreover, this study has analyzed the problem of the overvoltages that can be seen in the network with high adoption of self-consumption. The study concludes that in the so-called “instantaneous consumption” scenarios no voltage problems are detected, however in the “deferred consumption” scenarios high voltage values are readily observed even for low adoption levels with significant geographic concentration.

The results obtained indicate that although voltage control by PV inverters connected to the MV network is an effective solution to reduce overvoltages, the trade-off is an increase in network losses, both in the medium voltage network and the transmission network that feeds it. In addition, more investment would be needed both by self-consumption, needing an inverter of higher capacity as well as by network operators, having to ensure greater reserves of reactive power to supply the reactive demand that enable voltage control. In short, the downside of voltage control is a loss of energy efficiency for the entire system.

Finally, the annual analysis has also allowed us to study the effects associated with the variability of solar irradiation. All the observed effects, namely the variation of losses and the change in voltages, change when variability is taken into account and are more significant in the summer months than in winter. In addition, these changes are more important in areas with lower levels of irradiation, due to the greater relative size of the photovoltaic panels used. In all cases, the changes related to the variability of irradiation do not change the conclusions of the study, they tell us that real-life conditions are going to be worse for losses and voltages.

# 8 Future Work

The network model developed for the project GEDISPER from high voltage to low voltage for Murcia, Biscay and Madrid, can serve as a basis for developing other projects that require a detailed model of transmission and distribution networks. Here are some possibilities for potential studies.

## 8.1 Optimal location of storage elements

The integration of renewable inherently intermittent energies into the electricity system requires the gradual incorporation of elements that provide flexibility to the operation of the electrical system. Flexible generation and storage are technologies that can provide this flexibility. Given the storage technologies available, electrochemical batteries or accumulators have the characteristic of being modular, allowing them to be installed both in high voltage networks, transport level, as in low and medium voltage distribution level.

Using the model developed for the GEDISPER project, the different effects on networks of transmission and distribution that depend on the location of storage elements can be analyzed: (1) Installing the batteries near centralized generation, regulating the intermittence in origin; (2) Battery Installation in distribution networks or, where appropriate, within consumer installations, regulating the intermittence near the point of consumption.

This study should also consider the influence of the level of penetration of renewable energy, which may be the main parameter to determine the optimal storage location. For example, for low penetrations of renewable energy, it is possible that the optimal storage location is in distribution networks, close to customers, to reduce the effect of peak demand. Moreover, for high penetrations of renewable energy, it is possible that the optimal storage place is next to renewable sources, to moderate power flows and losses.

## 8.2 Network development to integrate loads Electric Vehicle (EV)

The electrification of road transport is one of the main tools available for reducing greenhouse gas emissions worldwide. The introduction of the electric vehicle as a technological solution requires the development of charging infrastructures. Charging can be fast or slow, depending on the maximum power at the point where the vehicle is connected.

The network model developed for the GEDISPER project would allow an analysis of the technical impact of EV charging, depending on the level of adoption and the degree of concentration of the charging and depending on the fast or slow type.

Defining a hypothesis of gradual adoption of VE in different areas of the network, and defining the type of charging (fast or slow) areas of the network could be identified where a greater impact on the operation of the network is to be expected. The model would also allow simulating what operational measures or, if necessary, reinforcements of infrastructure are needed.

In the case of available models of deployment costs and operating systems intelligent recharging called, they could be established optimization studies in which sopesase the best alternative to choose for each network zone, either a reload smart guy, While reinforcing the electrical infrastructure.

## 8.3 Identification of non-technical losses

Leveraging the network models developed for the project GEDISPER it would be possible to estimate the technical losses that should be occurring on the network in each of the scenarios studied. This estimate, compared with the measured values of losses, would locate the areas there is a greater concentration of non-technical losses.

## 8.4 Control of voltage in distribution networks

The penetration of distributed generation in distribution networks has an effect on the losses in the network, as shown in this report. Another of the effects of distributed generation penetration in distribution networks is an increase of voltages in power injection nodes that can cause allowable operating limits to be exceeded.

With the models developed for this study, and at different stages of penetration of distributed generation, one could consider an analysis of the possible measures that fix the changes in voltage levels.

# 9 References


[1] OFGEM, Electricity distribution losses. A consultation document, Office of Gas and Electricity Markets, Enero 2003

[2] Martín M.L y Ramati O.H., Pérdidas de energía en la distribución, Comisión de Integración Eléctrica Regional (Res. 89-36 XXV-R-CC), Montevideo, 1991

[3] MIT, The Future of Solar Energy. An Interdisciplinary MIT Study. 2015. Disponible en: http://energy.mit.edu/wp-content/uploads/2015/05/MITEI-The-Future-of-Solar-Energy.pdf

[4] V. H. M. Quezada, J. R. Abbad, T. G. S. Roman, Assessment of Energy Distribution Losses for Increasing Penetration of Distributed Generation, IEEE Transactions on Power Systems, Vol. 21, No. 2, pp. 533-540, May 2006

[5] D. Pudjianto, P. Djapic, J.Dragovic, G. Strbac, Grid Integration Cost of PhotoVoltaic Power Generation, Imperial College London, September 2013. Disponible en: http://www.pvparity.eu/fileadmin/PVPARITY_docs/public/PV_PARITY_D44_Grid_integration_cost_of_PV_-_Final_300913.pdf

[6] Real Decreto 900/2015, de 9 de octubre, por el que se regulan las condiciones administrativas, técnicas y económicas de las modalidades de suministro de energía eléctrica con self-consumption y de producción con self-consumption. BOE núm. 243, de 10 de octubre de 2015, páginas 94874 a 94917.

[7] REE, Informe del Sistema Eléctrico Español 2014. Disponible en: http://www.ree.es

[8] PVGIS. Disponible en: http://photovoltaic-software.com/pvgis.php

[9] IDAE, Consumos del Sector Residencial en España. Resumen de Información Básica. Disponible en: http://www.idae.es/uploads/documentos/documentos_documentacion_basica_residencial_unido_c93da537.pdf

[10] Ciemat, Base de datos ADRASE (Acceso a Datos de Radiación Solar de España). Disponible en: http://www.adrase.com/