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Assessing the Impact of Distributed Energy Resources in the Energy System

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Contents

1. RESUMEN

Actualmente el modelo energético mundial está centralizado y basado en los combustibles fósiles como el petróleo, carbón y gas natural, España no es una excepción. Este escenario contribuye significativamente a la insostenibilidad global debido a la contaminación y las emisiones de CO2 y por otra parte, al rápido agotamiento de los limitados recursos de combustibles fósiles.

Este proyecto analizará el papel que pueden jugar los recursos energéticos distribuidos (DER's) como la energía solar fotovoltaica en el sector energético español , teniendo en cuenta , entre otras cuestiones , los impactos en las redes de distribución .

La generación distribuida (DG) está aumentando en todo el mundo, y se prevé que en el futuro va a jugar un papel importante en el sistema energético. La generación distribuida se encuentra en las redes de distribución cerca de los consumidores o incluso en el lado de los consumidores. Por lo tanto, la demanda neta que se suministra a través de las redes de transmisión y distribución puede disminuir, lo que permite posponer el refuerzo de las redes existentes.

Este trabajo propone un método para evaluar el impacto de la generación distribuida en las redes de distribución. A partir de varios escenarios para solar fotovoltaica, caracterizados por diferentes niveles de penetración y costes, nos llevaran a un análisis simplificado de cómo afectará esto al sistema energético español.

El objetivo de este proyecto es basarnos en el modelo MASTER (Modelo de Análisis de Energía Sostenible) el modelo desarrollado por el IIT para cuantificar el impacto de los recursos energéticos distribuidos (DER's) en el futuro sistema energético. Entre las principales tecnologías DER's, el proyecto tendrá en cuenta la energía solar fotovoltaica.

En las redes de distribución de energía, el coste óptimo junto con las pérdidas de potencia más bajos se puede lograr mediante el aumento de la utilización de los sistemas descentralizados, distribuidos con unidades generadoras más pequeñas situadas cerca del punto de consumo , por lo tanto, reducir al mínimo las pérdidas de transporte de energía.

Inicialmente, en 2008 la mayoría de la capacidad instalada era de terminales de gas y carbón. Para evaluar el impacto de cada tipo de tecnología y el coste de la energía en 2020, ya que nuestro modelo es una optimización de costes, el impacto en los costes de red a distinto nivel de penetración se analiza, se centra en la tecnología fotovoltaica, ya que este es un ejemplo perfecto de una renovable suministro de energía que se puede instalar ya sea de una manera centralizada o descentralizada. Los costes de la red se basan en la nueva capacidad instalada, tomando en consideración explícita los diferentes costes que intervienen para cada unidad de generación que optimiza en el largo plazo, que surge de un estudio de caso en el campo de la energía fotovoltaica centralizada y descentralizada. Mediante la introducción de estas características operativas, tenemos la intención de desarrollar un modelo detallado en términos de costes y restricciones. Y finalmente, analizar el impacto de los resultados en el Sector Energético Español, examinando los diferentes efectos sobre instaladas capacidades, costes y pérdidas.

Nuestro enfoque a continuación muestra las siguientes diferencias o propias contribuciones:

- Una función objetivo transporte que incluye una ecuación de modelado para representar los costes de red (tanto fijos como las pérdidas) .
- La introducción de nuevas restricciones para los costes de distribución.
- Modelado capacidad instalada de la energía solar fotovoltaica, lo que afecta a las opciones de instalación para el MAESTRO SO.
- Competitividad entre PV centralizada y descentralizada.

Este nuevo modelado refuerza el modelo inicial MASTER para satisfacer la demanda exacta, mediante la reducción de costes a través de la instalación de recursos distribuidos. Por esta razón, se selecciona la energía solar fotovoltaica como una tecnología de referencia.

Con el fin de llevar a cabo el estudio de costes, se crea una función de los costes de distribución de la red. Para modelar dichos costes de la red de distribución, se consideran:

1- Pérdidas eléctricas, que se refiere a la cantidad de electricidad que se pierde en la transmisión y distribución. Estos sólo serán referidos para PV distribuida. Hasta un 18% de nivel de penetración, las pérdidas serían un valor negativo. Esto significa que para esta cantidad de capacidad de PV, no habría un ahorro en costes de la red. Las pérdidas podrían aumentar linealmente a medida que la generación distribuida crece.

2- Los costes de red fijos, se refieren a los costes de las nuevas instalaciones para llevar energía a los consumidores. Estos costes son impulsados principalmente por la combinación de perfiles de demanda y generación, así como por los lugares donde se producen la demanda y generación. Costes de red centralizadas serán 15 % más barato que los costes de red distribuidos.

Los costes totales de la red serán la suma de estas dos características. Vamos a tener que agregarlos al coste de la función existente en el modelo para cuantificar la variación de la demanda y generación.

Adición de la función de costes afectará a los costes totales de la modelo, y de la misma manera, la oferta de cada tecnología de generación instalada. Por lo tanto, varios estudios de casos se llevan a cabo.

En las redes de distribución, el punto de coste óptimo y las pérdidas de potencia más bajos se pueden lograr mediante el aumento de la utilización de sistemas distribuidos con unidades generadoras más pequeñas situadas cerca de consumo, por lo tanto, los costes de distribución dependerán sobre todo en el nivel de penetración. La penetración es una medida de la cantidad de DER en comparación con el recurso total de generación en un sistema de potencia. Esto se aplica a toda la red interconectada. Costes de red distribuidos aumentarán linealmente a medida que aumenta la cantidad de FV instalada distribuidos. Los costes de la red se basan en el nuevo problema de la capacidad instalada tomando en consideración explícita los diferentes costes que intervienen para cada unidad de generación que optimiza el servicio a largo plazo, que surge de un estudio de caso en el campo de la energía fotovoltaica centralizada y descentralizada.

El primer caso de estudio es la determinación del impacto de la energía fotovoltaica distribuida como una generación más cara, en la red y todo el sistema energético. Sectores de demanda pueden consumir más de un tipo de energía, que genera competitividad, así como la flexibilidad entre las tecnologías. Se muestra un incremento de aproximadamente el 20% de la demanda de 2020. El gas se reduce con el fin de producir energía solar fotovoltaica y otras energías renovables como la eólica, crecerá alrededor del 5%. La energía nuclear se estima también que reducirse durante este período de tiempo, ya sea como cogeneración y biomasa aumentará. Generación térmica solar también se eleva como una tecnología de generación opcional. En cuanto a los costes totales del modelo, debido a la intermitente penetración renovable, el incremento en la operación y mantenimiento (O & M) es casi insignificante. En cuanto a los costes de inversión, que variarán en función de la capacidad instalada modelado y afectarán a otros costes variables posteriores, que incluyen los costes de emisión, las pérdidas y los nuevos costes de red modelados para la energía solar fotovoltaica.

El segundo estudio de caso se centra en la determinación de la competitividad de costes entre PV centralizada y descentralizada. Se decidió ejecutar 3 escenarios diferentes para nuestro estudio. En el escenario 1, los costes de inversión distribuidos son 30 % más altos que los costes de inversión PV centralizados. Para el escenario 2, los costes de inversión PV distribuidos se incrementan en un 15% más altos que los costes de inversión centralizados y el tercer escenario es para un mismo coste de inversión para cada generación fotovoltaica.

La variación de la energía fotovoltaica en el modelo va de 10 GW para el bajo nivel de penetración como el más alto nivel y 20 GW como el más alto nivel, fija como una restricción política. Centralizado es preferible contra distribuido por los bajos niveles de penetración, la instalación de la capacidad total que los modelos de restricción energética (10 GW). Para niveles de alta generación, es óptimo instalar ambos. Esto será debido al incremento en los costes de inversión de la energía fotovoltaica distribuida que en la mezcla de baja generación supera los costes de red, lo que será baja para distribuida. Como para alta generación de PV instalado (20 GW), se instalan los dos tipos de PV para satisfacer la demanda y para igualar los costes.

Para concluir, en cuanto a los resultados en los diferentes escenarios, fotovoltaica distribuida es competitivo frente PV centralizado para la inversión distribuido cuesta 15 % más alto que el coste de inversión centralizada, y para los mismos costes de inversión, será preferible instalar fotovoltaica distribuida para alta generación en el escenario 3, los costes de inversión son un factor de coste de baja generación ya que es preferible instalar la generación centralizada de 10 GW, como para alta generaciones, los costes de red superarán los otros, ya que se convierte representativa de 20 GW.

Teniendo en cuenta que la generación descentralizada nunca será superior a la centralizada, y que los costes de la red son más baratos para descentralizado, si sus costes se convierten en aproximadamente la misma en un punto de generación, que será más óptima para instalar fotovoltaica descentralizada y centralizada.

2. SUMMARY

Today, the world´s energy model is mainly centralized and based on fossil fuels like oil, coal and natural gas. Spain is not an exception to this model. This current scenario contributes significantly to global unsustainability due to pollution and CO2 emissions and; on the other hand, to the rapid depletion of the limited fossil fuel resources.

With a higher consumer interest on sustainability, and an increasing tendency to cut down on non-renewable sources of energy, renewable resources have seen their popularity rise very fast. Technological developments in the generation side together with growing environmental concerns have fostered the adoption of small-scale generation systems known as distributed generation (DG).

The objective of this project is to use the MASTER (Model for Analysis of Sustainable Energy Roadmaps) model developed by the IIT to quantify the impact of Distributed Energy Resources (DER´s) in the future Energy System for 2020. Among the main DER´s technologies, the project will consider solar PV. The focus of the present work is on the competition among centralized and decentralized resources in the whole energy sector, analyzing what role distributed energy resources (DER´s) like distributed solar PV can play in 2020 Spanish case taking as a based-case 2008 energy sector, considering among other issues, the impacts on distribution networks costs.

Initially in 2008 the majority of installed capacity was gas terminals and coal. To evaluate the impact of each type of technology on the energy cost in 2020, as our model is a cost optimization, the impact in network costs at different penetration level is analyzed, focusing on PV technology, as this is a perfect example of a renewable energy supply that can be installed either in a centralized or decentralized manner. The network costs are based on the new installed capacity, taking into explicit consideration the different costs that intervene for each generation unit that optimizes in the long-term, arising from a case study in the field of centralized and decentralized PV. By introducing these operational features, we intend to develop a detailed model in terms of costs and constraints. And, eventually, we analyze the impact of our results in the rest of the "Spanish Energy Sector", examining the different effects on installed capacities, costs and losses.

Our approach then shows the following differences or own contributions:

- New transport objective function that includes a modeled equation to represent network costs (both fixed and losses).
- Introducing new constraints for distribution costs.
- Modeling solar PV installed capacity, which affects installation choices for the MASTER SO.

- Competitiveness between centralized and decentralized PV.

This new modeling reinforces the initial MASTER model to satisfy the exact demand, but reducing costs by installing distributed resources. For this reason, solar PV is selected as a reference technology.

So as to carry out the costs study, a network distribution costs function is created. To model this distribution network costs, it is taken in consideration:

1- Electrical losses, referred to how much electricity is lost in transmission and distribution. These will only be referred for distributed PV. For the account of losses, figure 5 represents the cost of electric losses depending on the penetration level of distributed solar PV. Up to 18% of penetration level, losses would be a negative value. This means that for this amount of PV capacity, there would be savings in network costs. Losses would increase linearly as distributed generation grows.

2- Fixed Network Costs, refer to the costs of new installations to bring energy to consumers. These costs are mostly driven by the combination of demand and generation profiles, as well as by the locations where demand and generation occur. Centralized network costs will be 15% cheaper than distributed network costs.

The total network costs will be the sum of both these features. We will have to add them to the existing function cost in the model to quantify the variation in demand and generation.

Adding the costs function will affect the total costs of the model, and in the same way, the supply of each generation technology installed. Therefore, several case studies are carried out.

In distribution networks, the optimum cost point and the lowest power losses can be achieved by increasing the use of distributed systems with smaller generating units placed close to consumption, therefore distribution costs will depend mostly on the penetration level. Penetration is a measure of the amount of DER compared with the total generation resource on a power system. This applies to the entire interconnected grid. Distributed network costs will increase linearly as the amount of distributed PV installed increases. The network costs are based on the new installed capacity problem taking into explicit consideration the different costs that intervene for each generation unit that optimizes a long-term service, arising from a case study in the field of centralized and decentralized PV.

The first study case is the determination of the impact of distributed PV as a more expensive generation, in the network and the whole energy system. Demand sectors can consume more than one type of energy, which generates competitiveness as well as flexibility between technologies. It is shown approximately a 20% increment in the demand for 2020. Gas is reduced in order to yield solar PV and other renewables such as wind, grow around 5%. Nuclear power is also estimated to be reduced during this period of time, whether as cogeneration and biomass will increase. Solar thermal generation also rises as an optional generation technology. As for the total costs of the model, due to intermittent renewable' penetration, the increment in operation and maintenance (O&M) costs is almost negligible. As for investment costs, they will vary depending on the installed capacity modeled and will affect other subsequent variable costs, that include emission costs, losses and the new network costs modeled for solar PV.

The second study case focuses on the determination of cost competitiveness between centralized and decentralized PV. It was decided to run 3 different scenarios for our study. In **scenario 1**, distributed investment costs are 30% higher than centralized PV investment costs. For **scenario 2**, distributed PV investment costs are increased in 15% higher than centralized investment costs and the **third scenario** is for a same investment costs for each PV generation.

The variation of PV in the model ranges from 10GW for the low penetration level as the highest level and 20GW as the highest level, fixed as a political constraint. Centralized is preferred against distributed for low penetration levels, installing the total capacity that the energy constraint models (10GW). For high generation levels, it is optimal to install both of them. This will be due to the increment in investment costs of distributed PV that at low generation mix overcomes network costs, which will be lower for distributed. As for high generation of PV installed (20GW), the two types of PV are installed to satisfy demand and to equalize costs.

To conclude, as for the results in the different scenarios, distributed PV is competitive vs. centralized PV for distributed investment costs 15% higher than centralized investment cost, and for the same investment costs, it will be preferable to install distributed PV for high generation in scenario 3. Investment costs are a cost driver for low generation as it is preferable to install centralized generation for 10 GW, as for high generations, network costs will overcome the others, as it becomes representative for 20 GW.

Given that decentralized generation will never be higher than centralized, and that network costs are cheaper for decentralized, if their costs become approximately the same at a generation point, it will be more optimum to install decentralized PV as well as centralized.

3. INTRODUCTION

Today, the world´s energy model is mainly centralized and based on fossil fuels like oil, coal and natural gas. Spain is not an exception to this model. This current scenario contributes significantly to global unsustainability due to pollution and CO2 emissions and; on the other hand, to the rapid depletion of the limited fossil fuel resources.

With a higher consumer interest on sustainability, and an increasing tendency to cut down on non-renewable sources of energy, renewable resources have seen their popularity rise very fast. Technological developments in the generation side together with growing environmental concerns have fostered the adoption of small-scale generation systems known as distributed generation (DG).

Distributed generation can offer an alternative planning approach to utilities to satisfy demand growth and distribution network security, planning and management issues.

The focus of the present work is on the competition among centralized and decentralized resources in the whole energy sector, analyzing what role distributed energy resources (DER´s) like distributed solar PV can play in the Spanish energy sector, considering among other issues, the impacts on distribution networks costs.

3.1 MASTER Model

This thesis is based on the model framework developed in MASTER SO model. According to Lopez Peña (2011) [LOP11], the MASTER SO is a partial equilibrium LP optimization model, whose goal is to supply the externally- given demand for energy services in all demanding sectors, complying with all technical and policy constraints, and maximizing the objective function, which is a measurement of energy sustainability. This approach entails a simplifying assumption: the model must satisfy each of these final energy demands.

The model uses a simplified representation of end-use sectors, based on processes that aim to satisfy this demand for final energy services. A process is simply a technology, which converts some inputs into some outputs and for doing so, has some technical constraints and creates some costs in the studied system. The processes can be primary energy processes, energy conversion processes or demand sectors.

Demand sectors (**DS**): represent the sectors in the economy that are demanding energy.

Energy transportation processes (**TE**): they represent the energy transportation and distribution networks that deliver this final energy to the correspondent demand sectors.

Energy conversion technologies (**CE**): these represent all the technologies used to transform primary energy sources into the final energy that, through the TE processes, is transported and distributed for final uses.

Primary energy sources (**PE**): the account for the total primary energy used in each moment, which can be domestic or imported.

The energy system's definition, once the processes (DS, TE, CE, PE) have been defined, is completed, allowing energy to flow among them. This is done through the definition of energy flows, which are the possible flows that energy can follow.

Figure 1 is a graphical explanation on how the processes are interconnected.

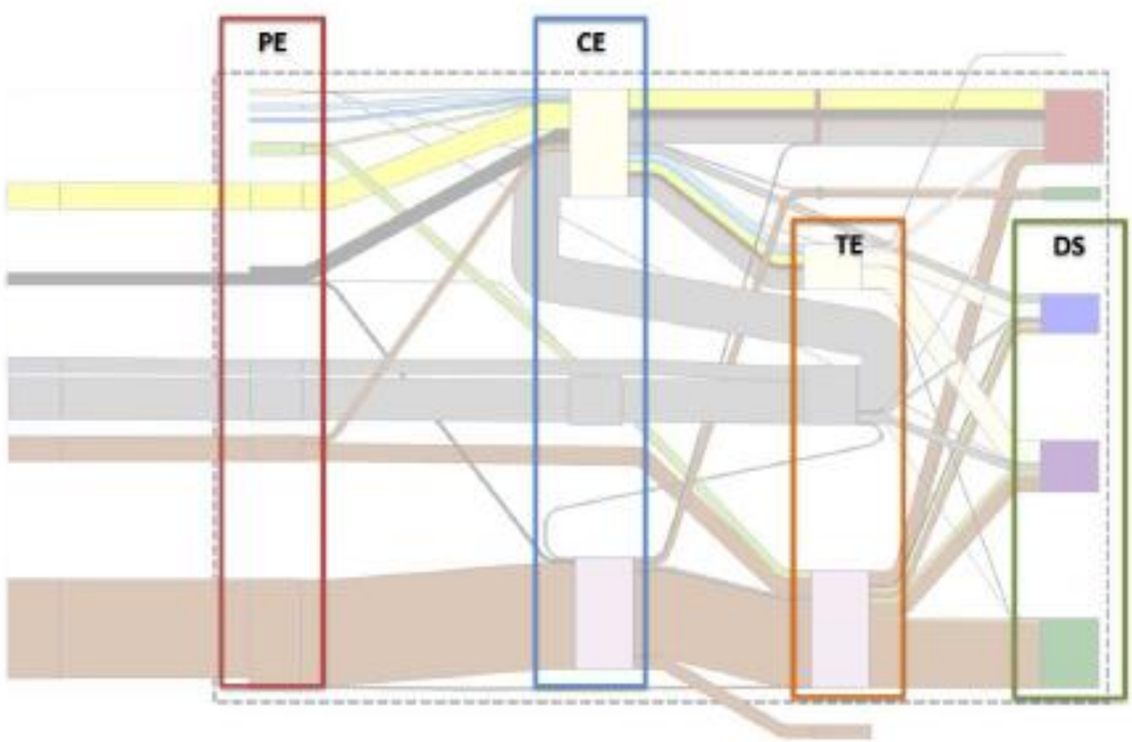


Figure 1. Energy flow graphical description
Source: PhDThesis A.LopezPeña

Once these measures have been characterized and introduced as data, the model chooses which of them to use, depending on the overall **cost minimization**. Those with the worst cost-benefit ratio will not be used. The model is run in GAMS and uses an Excel interface to import and export the model's inputs and outputs.

3.2 Decentralized vs. Centralized solar PV

Solar Photovoltaic (PV) energy can come from either distributed or centralized generation. Distributed generation consists of PV panels at distributed locations near consumption centers. Centralized plants are typically located at the point of best resource availability, and may be composed of PV or Concentrated Solar Power (CSP) technology. Currently there is a debate regarding which form of solar energy should be used to meet electricity. Distributed and Centralized solar power generation have their own strengths and weaknesses.

Distributed PV has the promise of supplying power during peak demand time and very close to the demand itself, thereby eliminating transmission loss. However, the intermittency of the panel output cannot be directly managed, and it is unclear how much distributed PV the electrical grid will be able to stand. On the other hand, centralized power generation may be located at regions where the resource is most available. But these stations require huge capital investments and may require new transmission lines to transfer power from the station to the consumption centers.

The need for more flexible electric systems, the changing regulatory and economic scenarios, the need of saving energy and the environmental impact are providing impetus to the development of distributed generation that is predicted to play an increasing role in the electric power system in the near future.

The purpose of this study is to focus on how distributed solar PV network costs affect the energy model, for 2020 Spanish case taking as a based-case 2008 energy sector.

4. STATE OF ART

The MASTER Model has been used to evaluate the impact of many technologies on networks costs and to determine the benefits and inconvenient that can be obtained from implanting those technologies on the network. Contributions on the model are explained later in detail.

Regarding the use of MASTER model to evaluate the impact of DERs on the network costs, Cossent et al (2010) [COSS11] made a quantification of the impact of distributed generation on distribution network costs in three real distribution areas. The distributed generation consists of installing small power generators situated geographically near to the consumption areas. Different scenarios of demand and generation were analyzed for each region. The computation of the distribution network costs was carried out by two large-scale distribution-planning models called reference network model (RNM).

Results showed that network costs, mainly investments, tend to increase as DG penetration increases. However, considerable differences among regions were found. DG penetration reaches a maximum of 500% in Kop van Noord (the Netherlands), 37% in Mannheim (Germany) and 33% in Aranjuez (Madrid). However, these values should not be directly compared for various reasons. The use of different simultaneity factors result in each kW of contracted power of load or installed DG capacity producing a different effect on power flows in each area. Additionally, the distribution of load and DG across voltage levels varies from one area to another. Other factors that proved to be at least as relevant as the DG penetration levels are: costs of lines/transformers, voltage level at which DG is connected, relative location of DG and loads, and temporal integration with demand (modeled by the simultaneity factors). The assumptions made regarding the contribution of DG and load to power flows in extreme conditions (simultaneity factors) were identified as being especially important. For some scenarios with very large DG penetration, the total increase in network costs caused by DG was lower the higher the level of demand was. On the other hand, in those scenarios with a low DG penetration level, costs tended to increase with demand.

Méndez et al (2006) [MEND06] propose a method to assess the impact of distributed generation (DG) on distribution networks investment deferral in the long-term. Due to the randomness of the variables that have an impact on such matter (load demand patterns, DG hourly energy production, DG availability, etc.), a probabilistic approach using a Monte Carlo simulation is adopted. Several scenarios characterized by different DG penetration and concentration levels, and DG technology mixes, are analyzed. Results show that, once initial network reinforcements for DG connection have been accomplished, in the medium and long-term, DG can defer feeder and/or transformer reinforcements.

Pudjianto (2013) [PUDJ13] aims at defining grid parity, i.e. achieving a stage of development of the PV technology, at which it is competitive with conventional electricity sources. The project will also develop strategies for supporting the PV sector after grid parity is reached. As a result, an increased PV penetration in EU electricity markets and grid will be accomplished at the lowest possible price for the community.

The objective of this project is to use the MASTER (Model for Analysis of Sustainable Energy Roadmaps) model developed by the IIT to quantify the impact of Distributed Energy Resources (DER´s) in the future Energy System. Among the main DER´s technologies, the project will consider solar PV. There are many ongoing discussions nationwide about the benefits and costs of distributed generation photovoltaics vs centralized solar power. This thesis adds to the MASTER model the distribution cost representation based on the discussed studies that examine the network cost evolution at different penetration levels of distributed generation.

5. MOTIVATION

Distributed Network Costs

The structure of electricity supply is changing from a centralized system towards a decentralized system. According to D. Pudjianto et al [PUDJ13], due to economic incentives and mature technologies, the number of small-scale PV systems installed in Spanish distribution networks has increased rapidly during the last years. The energy benefit of PV depends on which generation technology is displaced when PV electricity is supplied to the grid. One of the main issues related to photovoltaic systems is the overall system cost. Because distributed PV is typically placed close to the point of consumption, it can avoid important losses in the transport and distribution system, thus enhancing its value. However, in some situations, such as very high penetration levels where solar production is considerably greater than the original load, the reverse flow of power generated by distributed generation of PV could result in increased losses. As a result, when quantifying energy and capacity benefits and costs it is important to account for losses properly.

Therefore, it is critical to understand all the impacts of promoting distributed PV. This study analyses the hypothetical impacts of photovoltaic systems in terms of network costs: both fixed and variable (losses).

In distribution networks, the optimum cost point and the lowest power losses can be achieved by increasing the use of distributed systems with smaller generating units placed close to consumption, therefore distribution costs will depend mostly on the penetration level. Penetration is a measure of the amount of DER compared with the total generation resource on a power system. This applies to the entire interconnected grid.

To evaluate the impact of each type of technology on the energy cost, as our model is a cost optimization, the impact in network costs at different penetration level is analyzed, focusing on PV technology, as this is a perfect example of a renewable energy supply that can be installed either in a centralized or decentralized manner. The main discussion is related to the network costs that have been evaluated in the model.

6. METHODOLOGY

6.1 Running MASTER SO model

Our first step is to analyze the different inputs the model has, so as to understand the optimization that takes place.

In the model, demand is considered **inelastic**; electricity networks are modeled as a single node with average losses and cost factors. Demand sectors can consume more than one type of energy. This is an interesting aspect of the model, because it generates competitiveness as well as flexibility between technologies, and allows the model to choose whether it is preferable to generate heat with gasoline or consume solar energy, as an example of two end use services.

To supply that demand, the model counts with several generation technologies that are installed depending on the model's optimization. This is, once we run the model, it will install what is more economically optimal to satisfy the demand.

Figure 2 shows the **installed capacities** in the Spanish system in 2008. This is the base-case for further scenarios. We will refer to them as previous installed capacities in 2008. The color scale is in order with the diagram, ascendant.

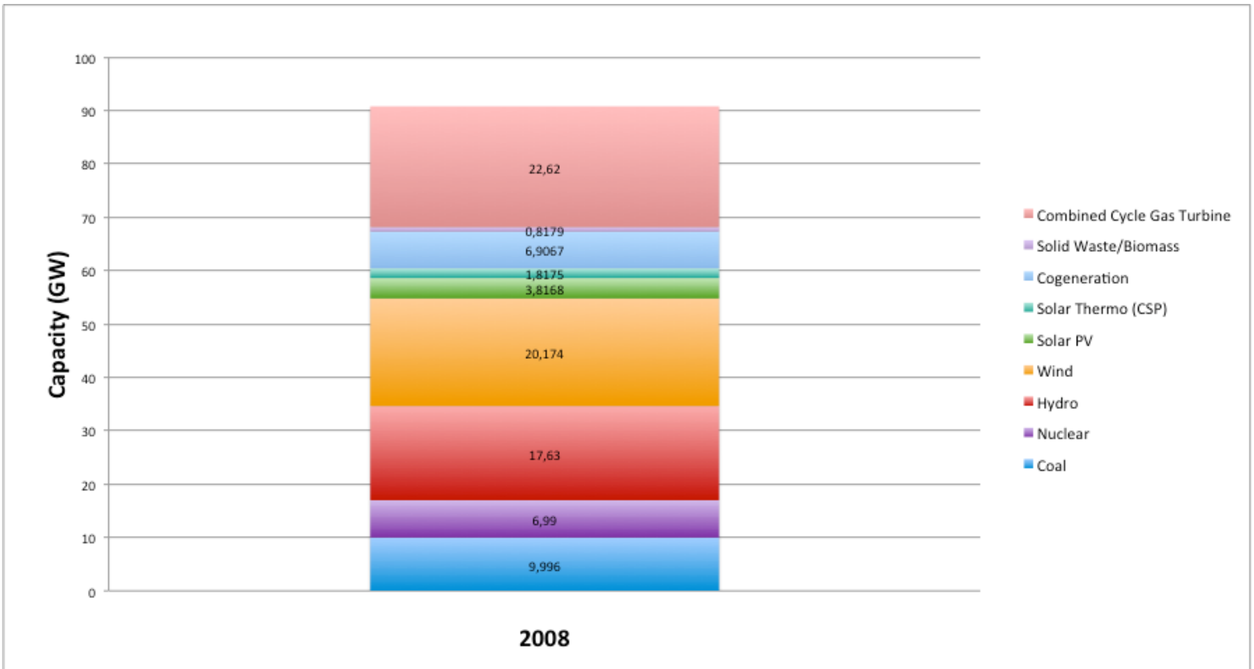


***Figure 2*. Energy installed capacities in Spain in 2008**
Source: Own source

It is shown that initially in 2008 the majority of installed capacity was gas terminals and coal. As we install distributed resources, it will then model as a **policy constraint** the need to install a minimum amount of solar PV as a case study. This will be discussed further on, with the different scenario cases proposed.

The model also operates with an objective function that minimizes **costs**. These are the main costs that account for the total aggregated energy supply, collected from an Excel interface to import and export the models inputs and outputs. So in an abbreviated way, figure 3 shows how the model will operate before introducing our own network costs.

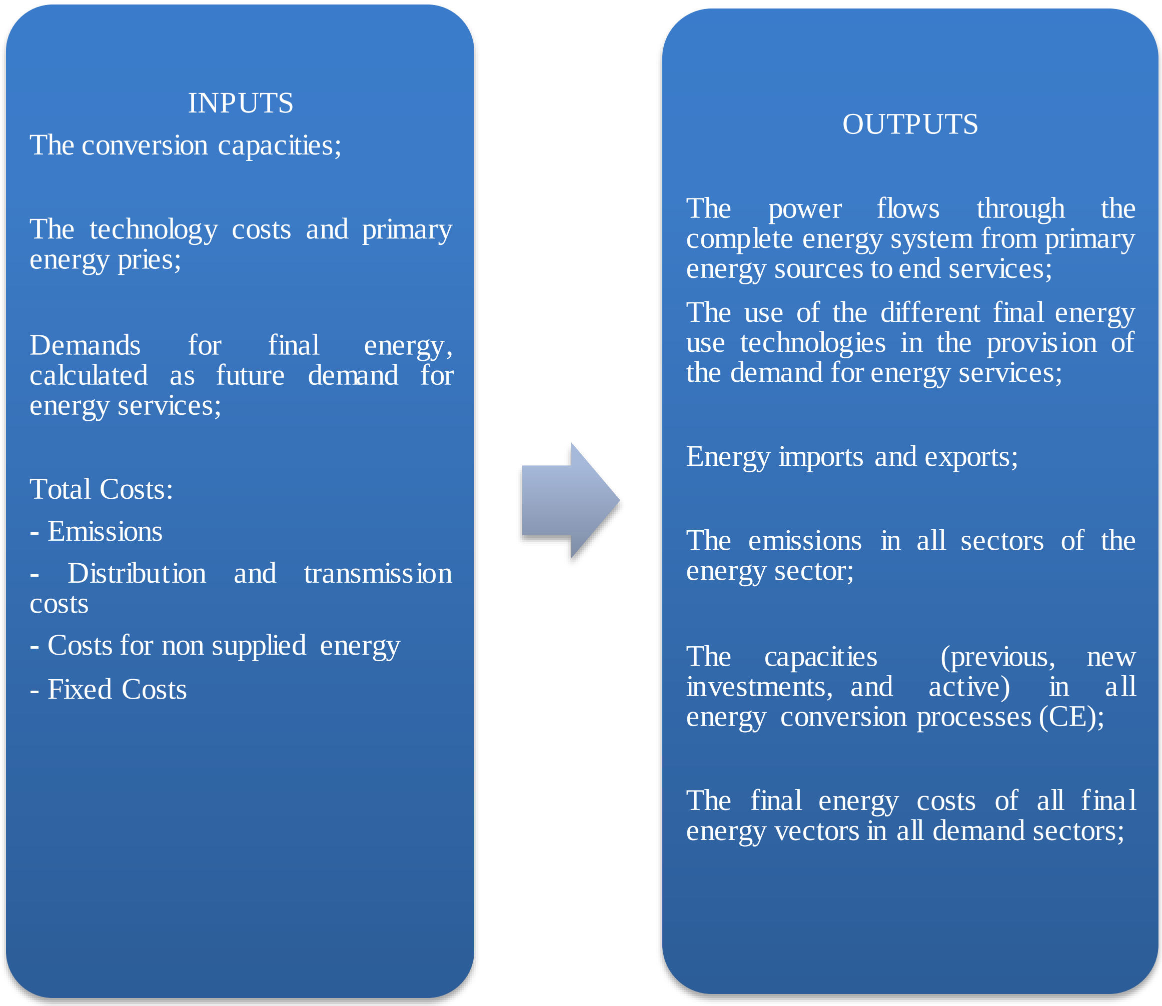


Figure 3. Inputs and outputs for MASTER model
Source: Own source

Once these measures have been characterized and introduced as data, the model chooses which of them to use, depending on the overall **cost minimization**. Those with the worst cost-benefit ratio will not be installed.

6.2 Contributions to the modeling in MASTER

One of the main parts of the project consists of creating a distribution network costs functions. To model this distribution network costs, it is taken in consideration:

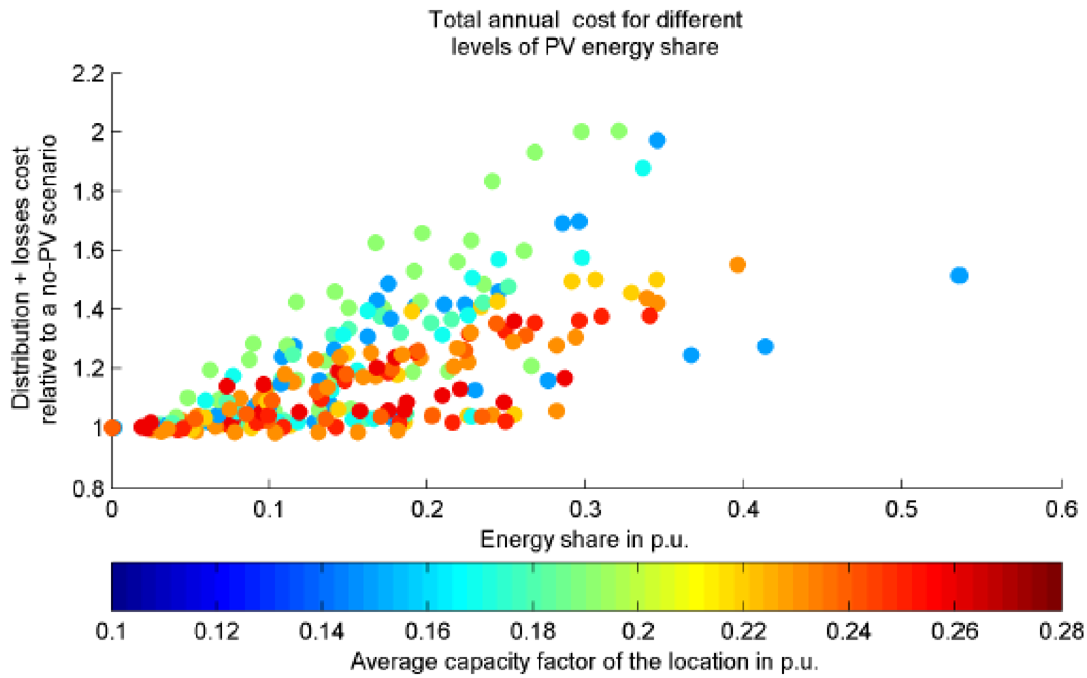
1- **Electrical losses**, referred to how much electricity is lost in transmission and distribution. These will only be referred for distributed PV.

2- Fixed Network Costs, refer to the costs of new network investment to bring energy to consumers. These costs are mostly driven by the combination of demand and generation profiles, as well as by the locations where demand and generation occur. Centralized network costs will be 15% cheaper than distributed network costs, as found in literature in [COSS11].

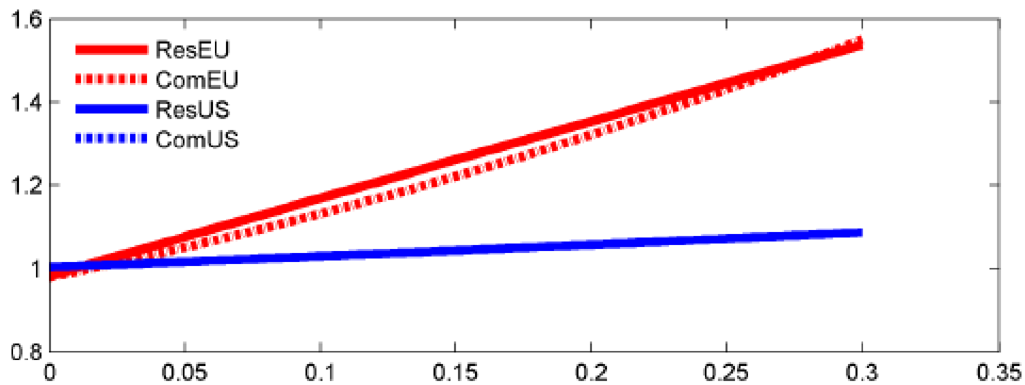
The total network costs will be the sum of both these features. We will have to add them to the existing function cost in the model to quantify the variation in demand and generation.

The network costs are based on the new installed capacity, taking into explicit consideration the different costs that intervene for each generation unit that optimizes in the long-term, arising from a case study in the field of centralized and decentralized PV. By introducing these operational features, we intend to develop a detailed model in terms of costs and constraints. It will not be purely theoretical, but results of the implementation of the approach will be studied and commented. And, eventually, we analyze the impact of our results in the rest of the "Spanish Energy Sector", examining the different effects on installed capacities, costs and losses.

According to [PUDJ13], built on previous studies and using a model-based approach, network costs can be represented graphically. Figure 4 reveals that significant penetration of PV generation can be a relevant cost driver in distribution networks, assuming that this sample adequately represents the diversity of networks that can be found in the electricity sector. Note that the x-axis in figure 4 corresponds to the ratio of annual PV generation to total load, and that a color scale has been used to identify the capacity factor of PV installations at the location considered in each particular simulation.



(a)



(b)

Figure 4. Network Distribution Costs for Decentralized PV

Source: Direct Costs Analysis related to Grid Impacts of Photovoltaics, Imperial College London

Distributed network costs will increase linearly as the amount of distributed PV installed increases. The network costs are based on the new installed capacity taking into explicit consideration the different costs that intervene for each generation unit that optimizes a long-term energy supply, arising from a case study in the field of centralized and decentralized PV.

For the account of losses, figure 5 represents the cost of electric losses depending on the penetration level of distributed solar PV. Up to 18% of penetration level, losses would be a negative value. This means that for this amount of PV capacity, there would be savings in network costs. Losses would increase linearly as distributed generation grows.

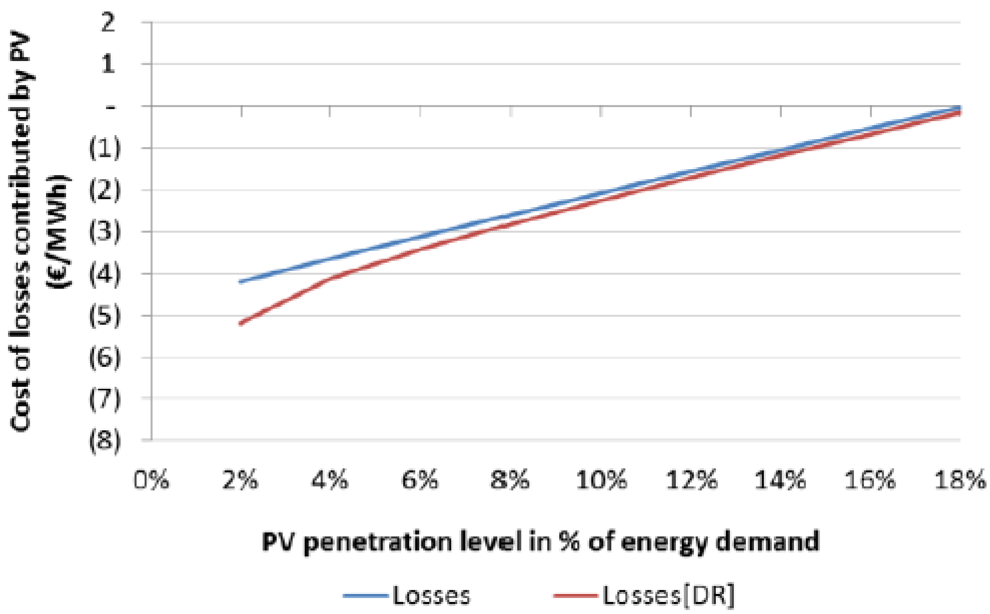


Figure 5. Network Distribution Costs for Decentralized PV
Source: Direct Costs Analysis related to Grid Impacts of Photovoltaics, Imperial College London

Based on the previous charts, it was decided to approach network costs representations as a curve, which will have a descending slope up to a certain level of penetration as a result of network losses, and an increasing slope as this penetration increases. As found in [MEND06], high levels of penetration of decentralized PV change network power flow modifying annual energy loss and cost of providing these losses. Although it is considered that distributed generation reduces system energy losses, it is shown that annual energy loss in distribution networks varies as a U-shape trajectory by increase in DG penetration level, with negative and positive slope tendency.

Figure 6 is a vague approximation of what it was expected to be modeled for distribution costs. The inflexion point shown in the curve will be referred as the penetration level in which costs will be differentiated in the modelling options to avoid nonlinear programming. It is been discussed further on.

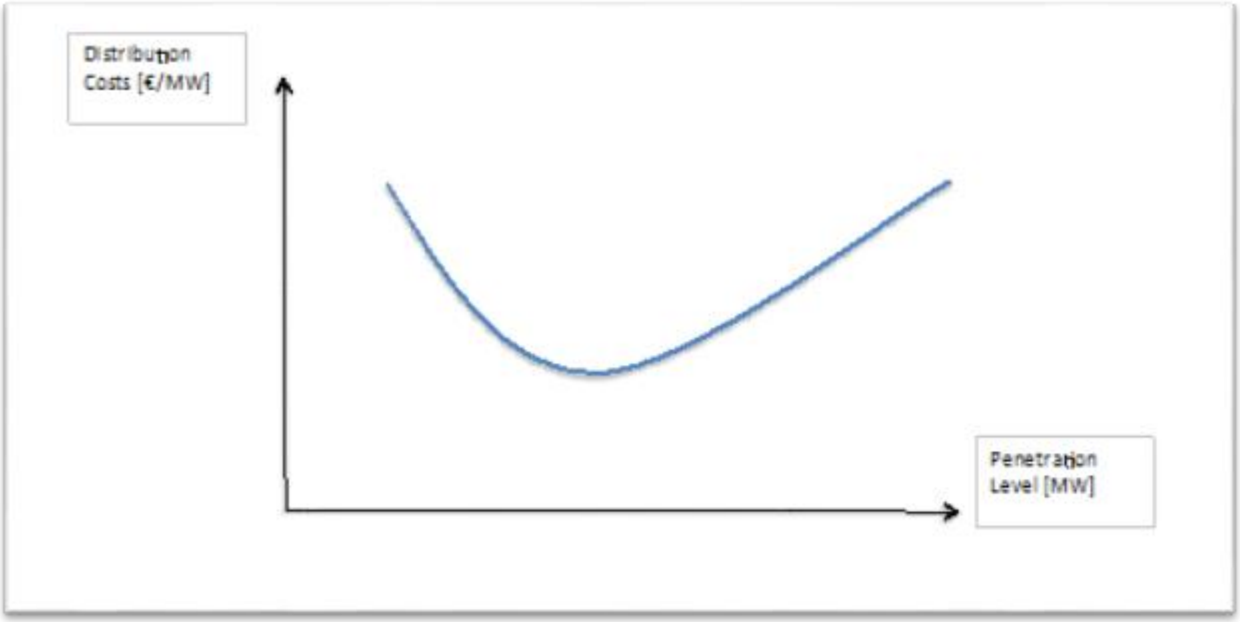


Figure 6. Aproximation for the PV Network Costs.
Source:Own Source

As compared to Lopez Peña (2011) [LOP11], our approach then shows the following differences or own contributions:

- New transport **objective function** that includes a modeled equation to represent network costs (both fixed and losses).
- Introducing **new constraints** for distribution costs.
- Modeling solar PV installed **capacity**, which affects installation choices for the MASTER SO.
- **Competitiveness** between centralized and decentralized PV.

So mainly, the first step was to develop, based on a previous analysis of figures 4 and 5, a function that models networks costs including energy losses, which will have a knee point in 5% of this penetration level (corresponding to 5000 MW capacity). For levels of penetration lower than 5% average, decentralized network costs will be null. For higher PV penetrations figure 7 represents the modeling of these costs.

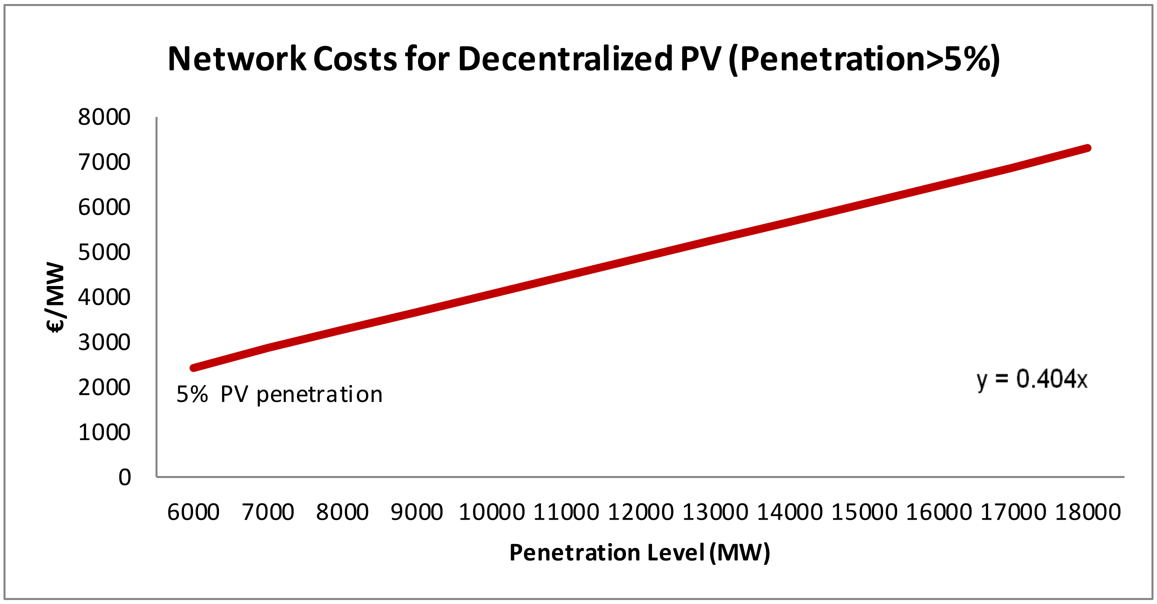


Figure 7. Network Distribution Costs for Decentralized PV, for lower penetration and high penetration levels. Knee-point in 5% penetration level.

Source:Own Source

$$Network\ Costs\ for\ Distributed\ PV = 0{,}404 \cdot Installed\ \ Capacity$$

The relation between PV installed capacity and network costs is referred to the costs function we will develop. Costs are expressed in €/MW. It is important to note that in this case, the minimum cost is not always obtained when the penetration level is low since the cost tends to decrease at certain extent when PV capacity increases.

For electric losses, figure 8 shows how they will also increase linearly for distributed PV increments. Losses are normally higher in distribution than in transmission and, within distribution, higher in residential areas than in industrial areas where voltage is higher.

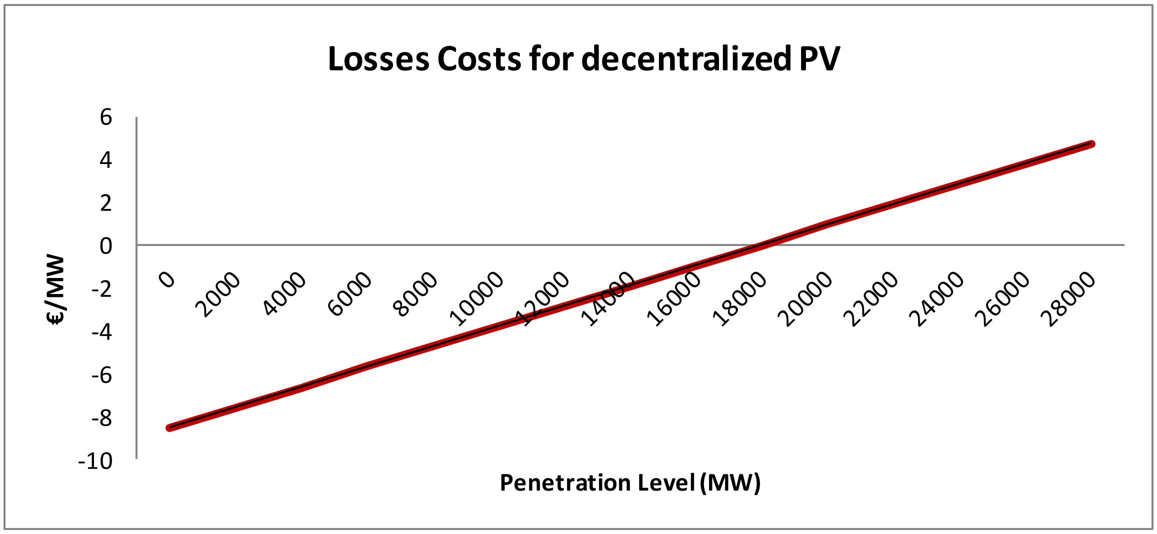


Figure 8. Network Losses for distributed PV, for lower penetration and high penetration levels. Knee-point in 5% penetration level.
Source:Own Source

As well as the distributed network costs, centralized network costs will also be linear with the penetration level and null for a penetration lower to 5%. Centralized transmission costs as shown in [MIT, 2011] are assumed 15% more expensive than distributed costs.

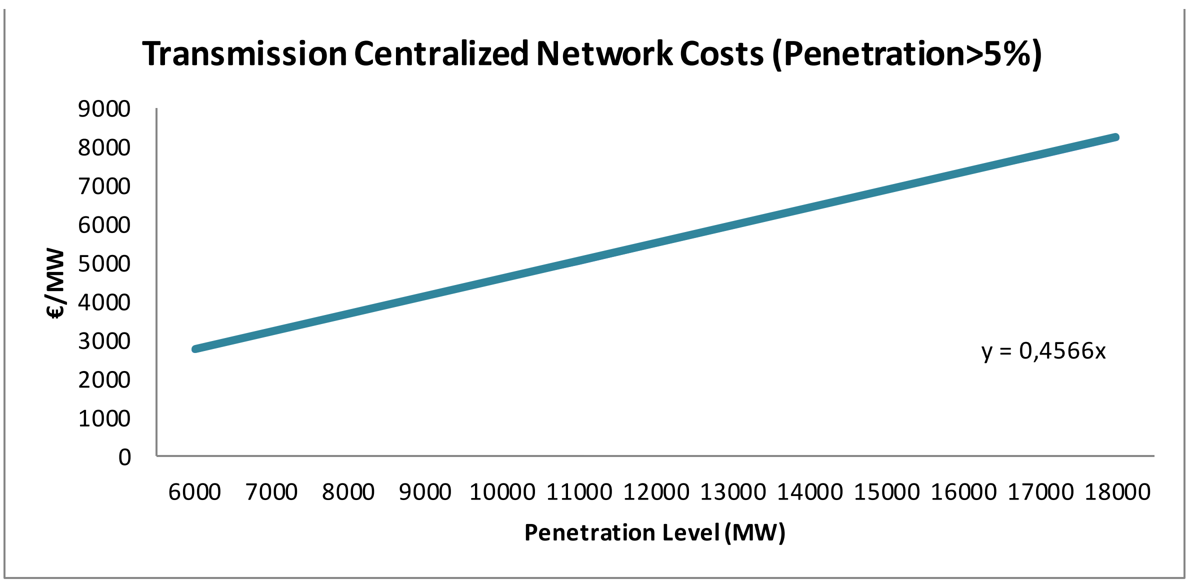


Figure 9. Distribution Network Costs for Centralized PV,
for lower penetration and high penetration levels. Knee-point in 5% penetration level.
Source:Own Source

$$Transmission\ Network\ Costs\ for\ Centralized\ costs = 0{,}4566 \cdot Installed\ Capacity$$

As mentioned previously, centralized PV network costs will be higher than decentralized costs in relation with the installed capacity in the system.

From figure 6, we define the tendency of transmission and distributed costs with two different slopes and differentiate from 5% of penetration level, so that in figures 7 and 8 it is specified which real costs would be included in the model. So the objective function at issue will have parameters assigned to these values obtained, such as the relation between network costs, penetration level or the quantity of losses for each generation described in both figures 6 and 7.
In figure 10, total network costs for solar PV are represented.

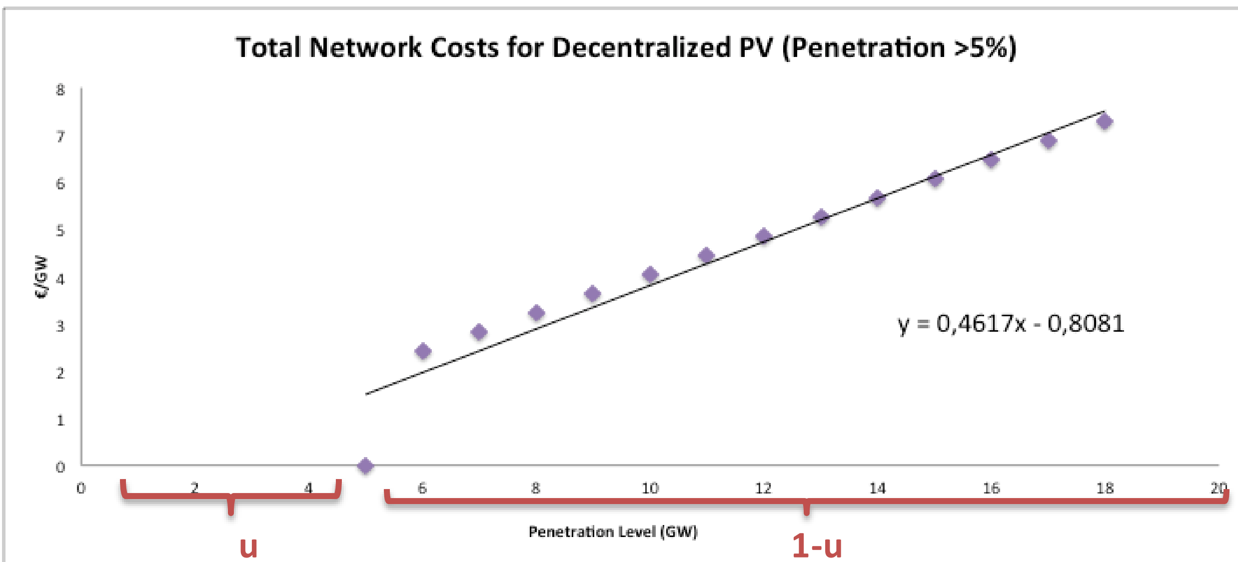


Figure 10. Total Distribution Network Costs for Decentralized PV,
Source:Own Source

$$Network\ Costs\ for\ Distributed\ PV = \mathbf{0{,}4617} \cdot Installed\ \ Capacity - \mathbf{0{,}8081}$$

As the model depends on the installed capacity and its costs, the function will also have to be modeled taking in consideration the quantity of PV installed. So the next step is to relate these functions, grouped in figure 10, to the optimization with an LP equation that integrates network costs for decentralized and centralized PV separately and that satisfies further energy constraints.

To discuss the modeling, the equation for only decentralized solar PV network costs is processed as an explanation of the different steps. This function integrates all networks costs for solar PV, for the model to differentiate between centralized and decentralized PV costs and optimize when it's preferable to install one or another.

As the model uses a simplified representation of end-use sectors, based on processes, the distribution costs formulation is also to be defined for a CE (conversion energy process) for PV, so that it is specified for only photovoltaic and the capacity installed is controlled directly from the equation designed. To take into account the energy flow between processes, where for example losses are materialized, the model generates the variable **QPWR** (QuantityPoWeR flow) as the average quantity of energy flow, which will as well depend on the PV process and also the temporal variations.

NewInstalledCapacity is a positive variable referred to the amount of distributed PV the model will choose to invest for and for which it will determine costs. Figures 7, 8 and 9 represent the numerical parameters used to model the equation graphically. Regarding that distributed solar PV data is been discussed as an example to explain the methodology followed, the numerical parameters of the presented equation will base on Figure 7 and 9.

The relation between these two variables is non-linear, so to program in MASTER model, binary variables to design whether it has been modeled for high or low generation are required; this is said, from a mathematical perspective, a negative or positive slope, named as **variable u,** as shown in figure 10. This will be important for the account of losses because as mentioned before, up to 5% of penetration, losses are null for decentralized PV.

The first equation for network costs is designed as the following; Numerical parameters are the ones extracted from figure 10.

$$Network\ Costs\ for\ Distributed\ PV = \mathbf{0{,}404} \cdot Installed\ \ Capacity \cdot \boldsymbol{u} - \mathbf{0{,}8081} + \cdot (QPWR \cdot 0{,}0004722 - 8{,}4987(1 - \boldsymbol{u}))$$

To analyze the process by which we would assess the costs, we found the problem of binary variables having overlapped with positive variables, which is why the model is scheduled for MIP and not LP programming. The linearization of the equation is fundamental, because of the great difficulties in terms of computational capability that would appear with a non-linear approximation. More binary variables were created:

NU_DIS Denotes for linearization for binary variable u and new distributed PV installed capacity

UC_DIS Denotes for linearization for binary variable u and binary variable c

So the final equation is the following. This number was obtained after the several linearizations of contrasted data from [PUDJ13] as explained previously.

$$Network\ Costs\ for\ Distributed\ PV = \mathbf{0,404} \cdot Installed\ \ Capacity$$

- Equation for decentralized solar PV network costs:

Up to this point, numerical parameters and the positive variables are defined. Again the numerical parameters are extracted from figures 10.

$$\min\ Distributed\ PV\ Costs\ = 0.4617\ * \text{NewInstalledCapacity}$$

$$-(0.4617 *\ NU\_DIS) - 0.8081 * c + (0.8081 * UC\_DIS)$$

$$+(\ 0.0004722*\ \ sum\ all\ CE\ for\ Distributed\ \ PV\ for\ each\ TimePeriod +$$

$$QuantityPowerFlow(CE\ for\ Distributed\ PV, TimePeriod) - 0.8081 * c)$$

- Binary Variables

u Binary variable chosen to design positive or negative slope (high/low generation)

c Binary variable for logical propositions

Another major issue of the modeling, as well as the correct use of the logical propositions, comes with the constraints modeling.

- Constraints

The first one establishes the need for installed firm capacity.

The second one was modeled to limit or fixate the minimum amount of solar PV installed during the optimization process.

As well as the logical propositions to model and linearize.

These constraints were held satisfactorily by the implementation of what we previously named as the binary variables that control the optimization curve and the knee point designed for the optimization.

In **Annex 1** the realistic formulation basis is defined.

Solar PV network costs will be obtained with the previous formulation depending on the two parameters that can be modified. Those parameters are the new solar PV installed capacity that, as said before, is decided by the model depending on its investment costs. As well as the power flow, which the model will also define.

This new modeling reinforces the initial MASTER model to satisfy the exact demand, but reducing costs by installing distributed resources. For this reason, solar PV is selected as a reference technology.

7. CASE STUDIES

In this section, the effects of the different case studies which have demonstrated an iterative method to evaluate and calculate the optimum amount of each centralized and decentralized PV technology capacity with the electricity generation mix are discussed.

7.1 INSTALLATION OF DISTRIBUTED PV

One of the main parts of the project consists of accounting for the impact of distributed PV in the network and the whole energy system. Adding the costs function designed throughout the methodology, will affect the total costs of the model, and in the same way, the supply of each generation technology installed. As a first result, we measure the variation in the technologies' final installed capacity in 2020 as a final scenario and furthermore, the implication in the objective function that distributed PV network costs carry.

As this is an end-use model, it concentrates on demand sectors (**DS**) which represent the sectors in the economy that are demanding energy. Therefore, costs will make the model optimize the installed capacity to satisfy them.

Figure 11 shows the new profiles for the installed capacities, once distributed PV is installed, comparing generation in 2008 and 2020. As we can observe, there´s approximately a 20% increment in the demand for 2020.

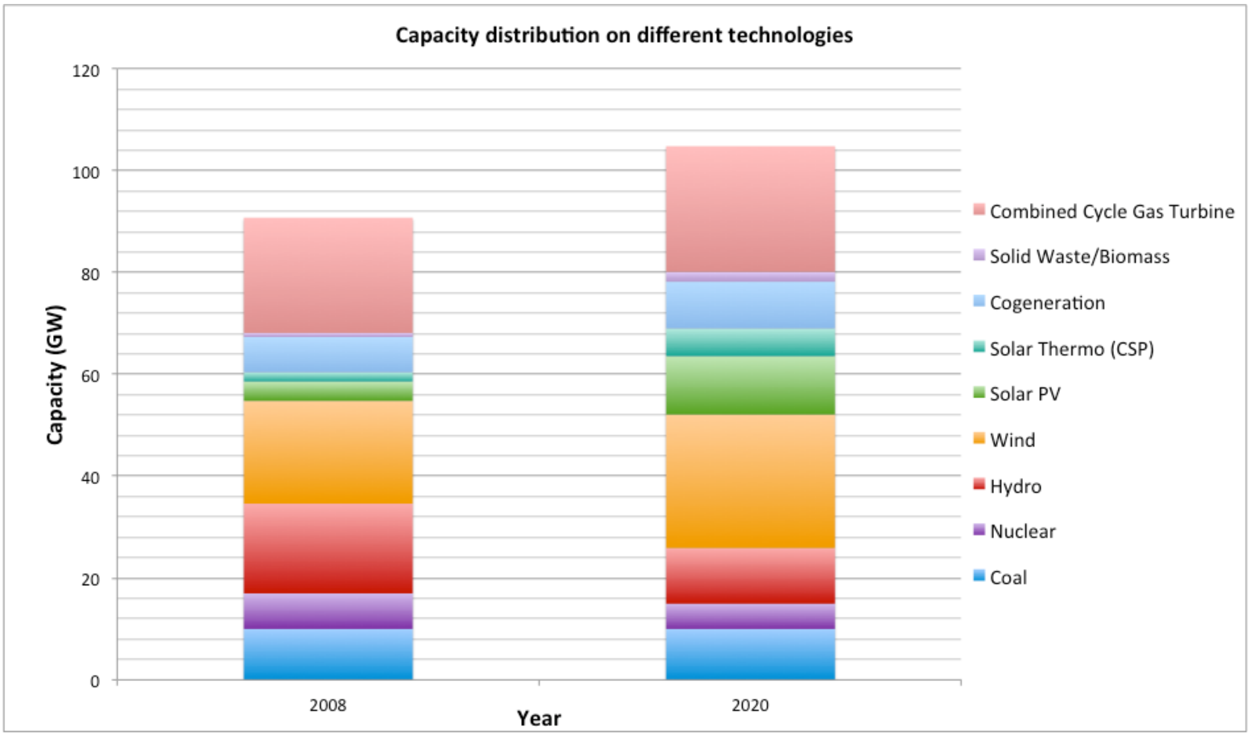


Figure 11. Comparison for installed capacities
Source:Own Source

As it was discussed earlier, demand sectors can consume more than one type of energy, which generates competitiveness as well as flexibility between technologies. Political energy constraints take part in this process so as to model the 2020 objective of increasing renewable share in the final energy use. In figure 11 we can observe how gas has been reduced to yield solar PV and other renewables such as wind, grow around 5%. Nuclear power is also estimated to be reduced during this period of time, whether as cogeneration and biomass will increase. Solar thermal generation also rises as an optional generation technology.

As for the total costs of the model, it is important to mention that due to intermittent renewable' penetration, the increment in operation and maintenance (O&M) costs is almost negligible. As for investment costs, they will vary depending on the installed capacity modeled and will affect other subsequent variable costs, that include emission costs, losses and the new network costs modeled for solar PV.

As including distributed resources affects the entire energy model, it is interesting to analyse a series of results regarding costs, emissions and capacities for scenario 1. As it is chosen to install a fixed quantity of PV, total invested network costs of the model will rise considerably as operation and maintenance costs (O&M) will decrease as shown in figure 12 for scenario 2, insignificantly in comparison with them, as a result of the additional variable network costs modeled.

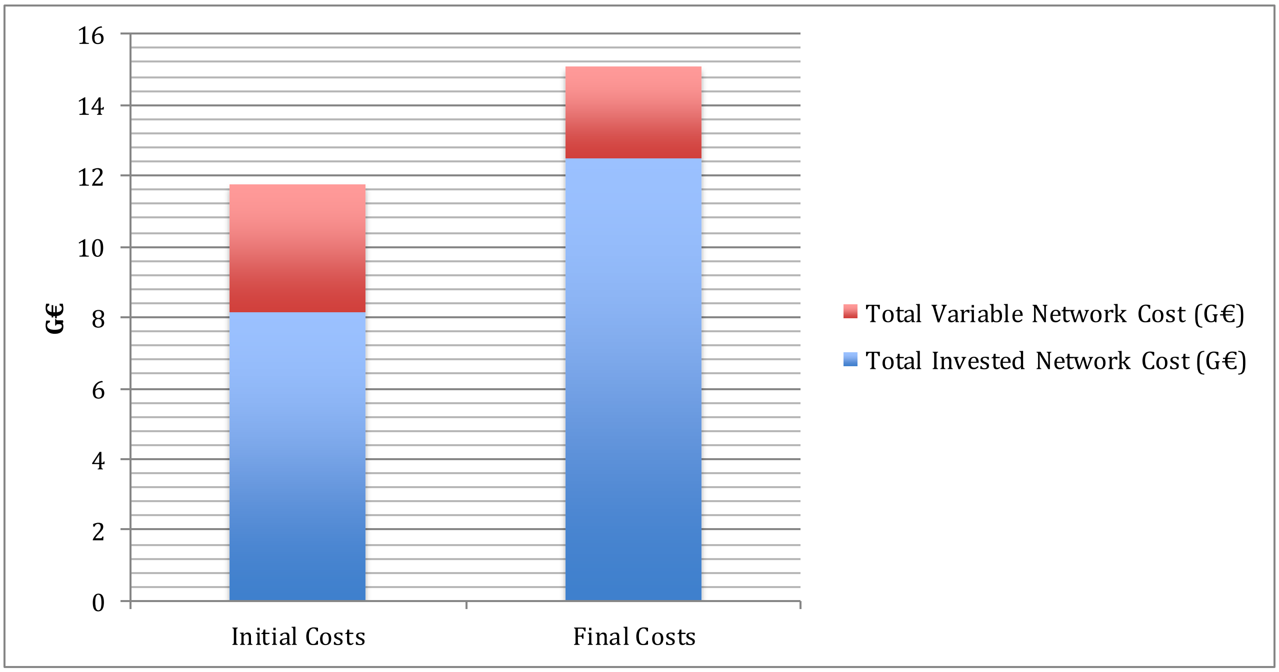


Figure 12. Total costs variation for the model in scenario 1
Source: Own Source

Adding distributed generation to the generating system also might benefit consumers by reducing wholesale electricity prices and reducing natural gas and other fossil fuel prices (objective function), although these consumer benefits would come at the expense of electricity generators and natural gas producers, respectively. Distributed generators at the distribution level can significantly impact the total capacity installed.

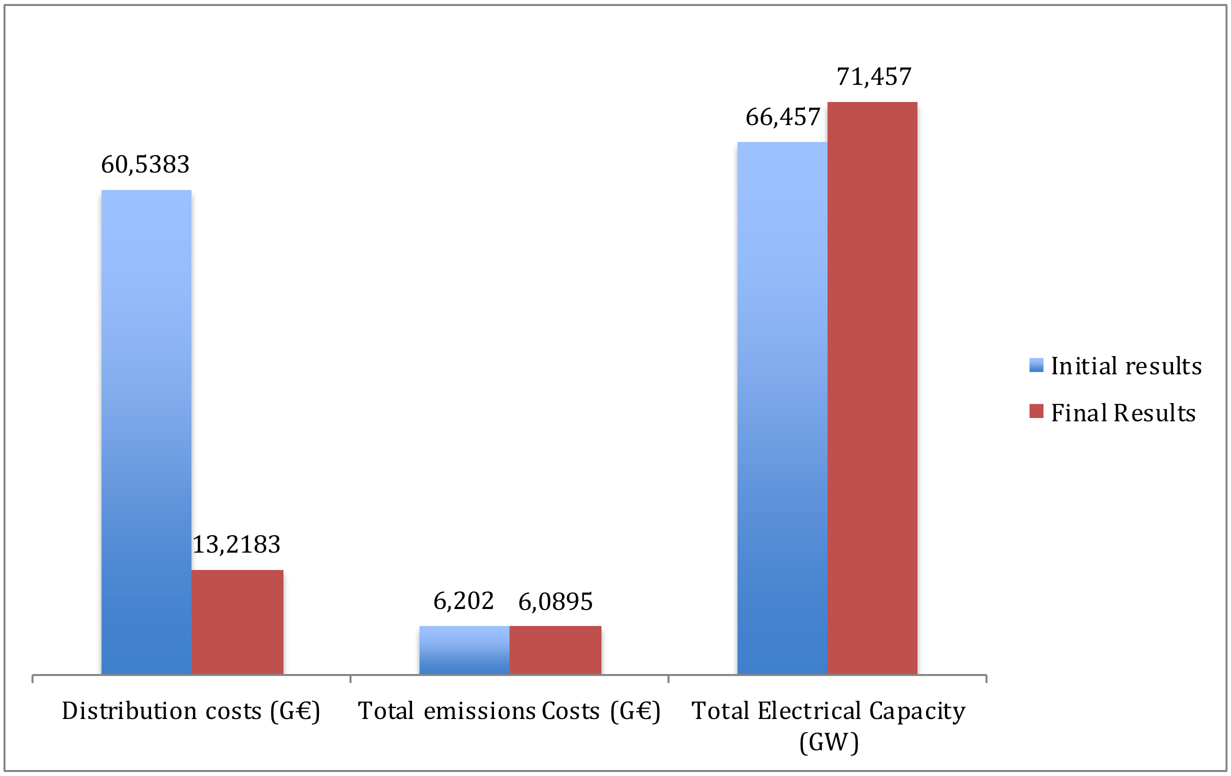


Figure 13. Results for the model with distributed PV in scenario 1
Source: Own Source

7.2 COST COMPETITIVENESS: Centralized vs Decentralized PV

Hence the presented data and values obtained throughout the project as a result of the study of centralized vs decentralized PV capacity installation, we run a series of **scenarios**. As the inflexion point was decided to be at around 5% penetration level, the variation of PV in the model ranges from 10GW for the low penetration level as the highest level and 20GW as the highest level, fixed as a political constraint.

To obtain data for figure 14, the procedure followed is to maintain total investment costs fixed for both centralized PV, as distributed investment varies for each scenario. With this and changing the amount of total PV capacity installed, the model gives back results for the function defined in the methodology with the chosen optimal capacity, centralized or decentralized PV according to the total, as well as the determined costs.

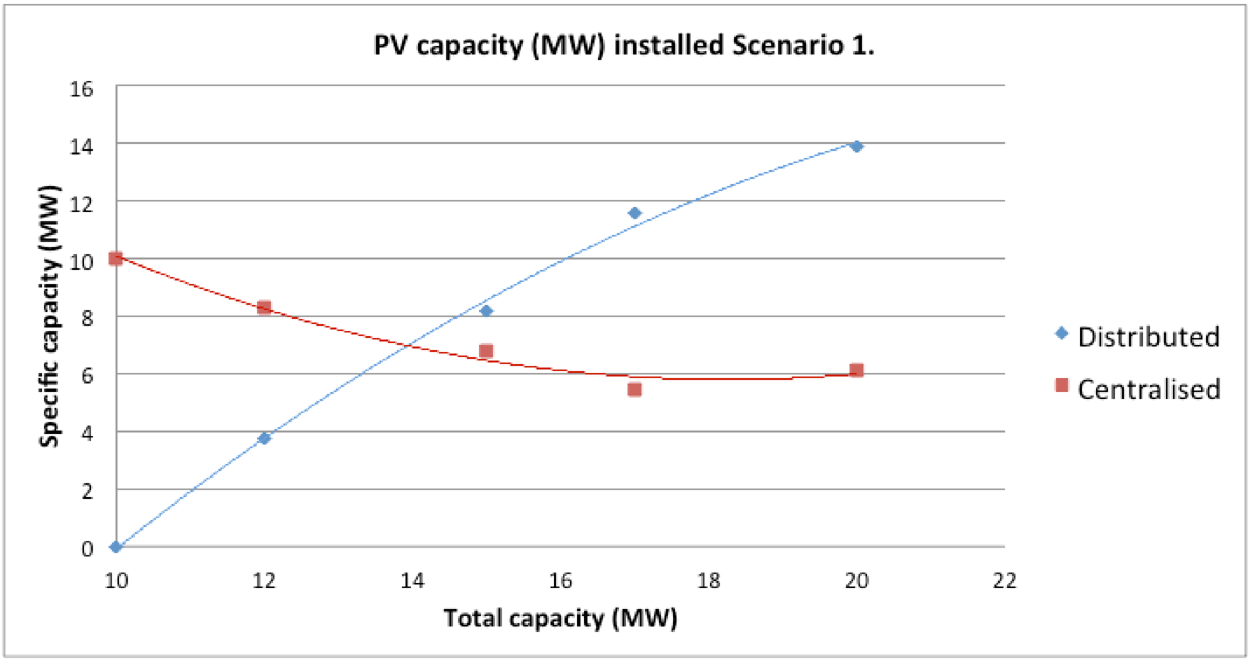


Figure 14. PV capacities for scenario 1
Source: Own Source

For scenario 1, as shown in figure 14, centralized is preferred against distributed for low penetration levels, installing the total capacity that the energy constraint models (10GW). For high generation levels, the model chooses to install both of them. This will be due to the increment in investment costs of distributed PV that at low generation mix overcomes network costs, which will be lower for distributed. As for high generation of PV installed (20GW), the model requires the two types of PV installed to satisfy demand and equalize costs.

For each scenario, figure 15 shows the PV installed capacities:

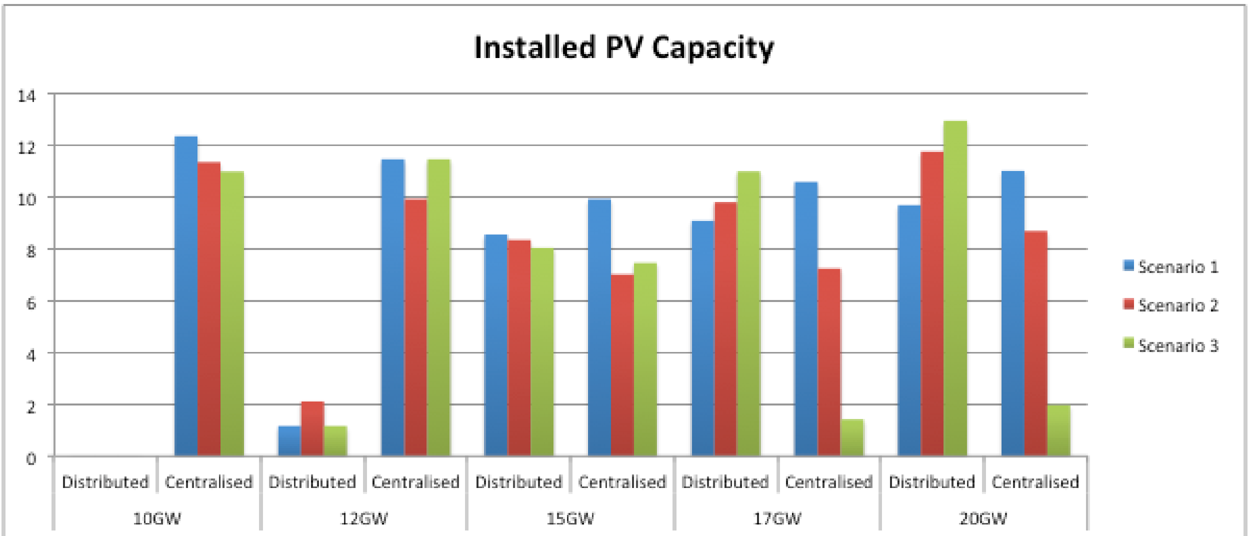


Figure 15. PV capacities for each scenario
Source: Own Source

Figure 16 shows the percentages of each centralized PV and distributed PV over the total amount of generation installed in this Scenario. As a result of the optimization model. Distributed generation increases considerably from a total of 15GW of PV installed, whereas centralized tends to decrease as distributed generation is installed, but remains nearly constant at the end.

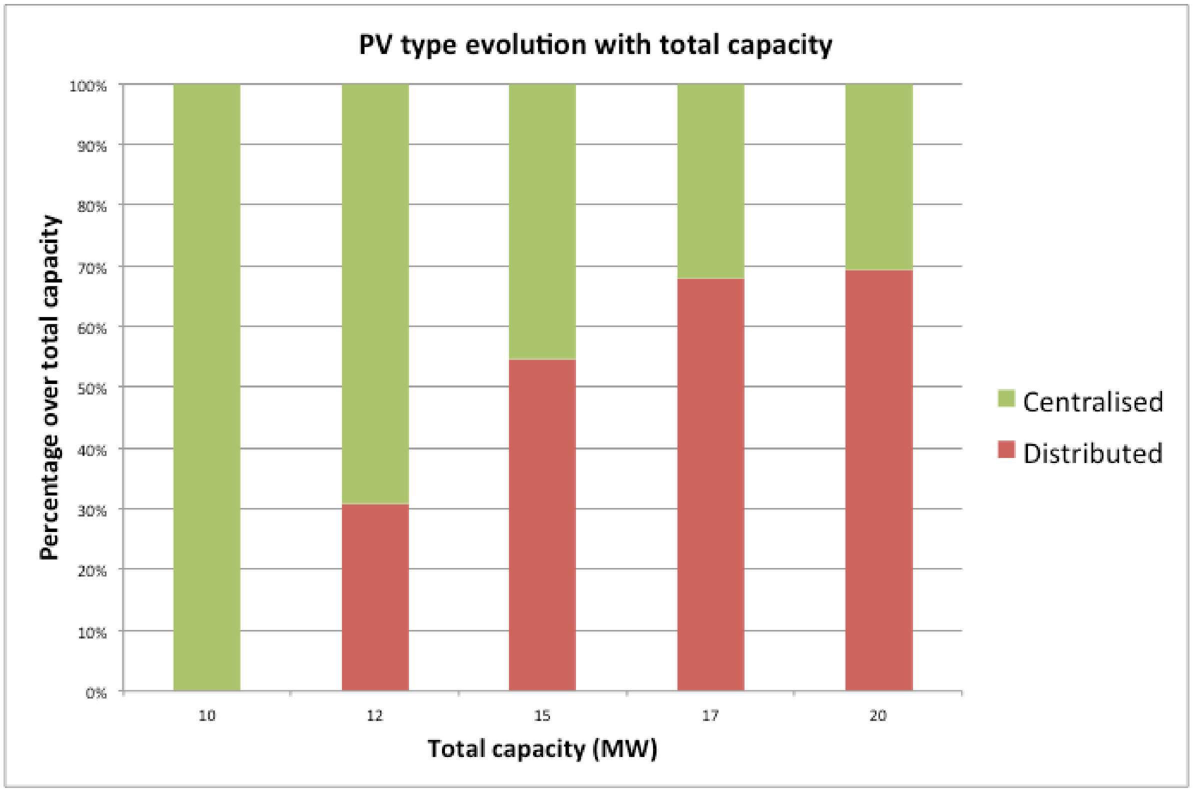


Figure 16. Percentages over total capacity in scenario 1
Source: Own Source

So the main costs driver for low generation would be investment costs as well as for high generation, as network costs depend on installed capacity, they will determine the final costs.

Therefore, it was decided to run 3 different scenarios for our study. In **scenario 1**, distributed investment costs are 30% higher than centralized PV investment costs as found in [MIT15]. For **scenario 2**, distributed PV investment costs are increased in 15% higher than centralized investment costs and the **third scenario** is for a same investment costs for each PV generation.

In figure 17, the three scenarios are presented with the different investment costs defined.

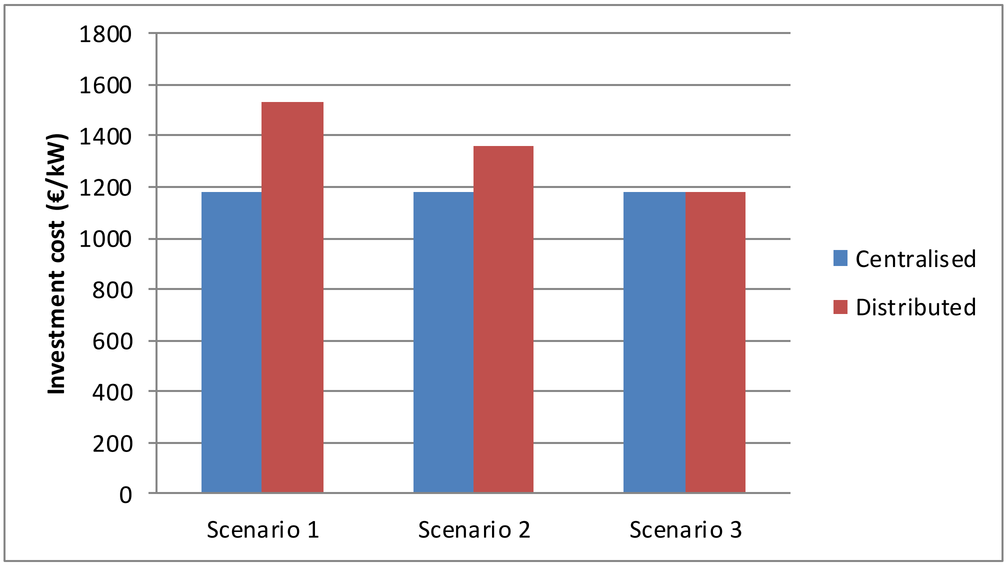


Figure 17. Investment costs for each scenario
Source:Own Source

Low penetration levels do not represent significant changes between scenarios; the model mainly decides to always install centralized PV. As for high penetration levels, in scenario 1 where the price increment is the highest, once 15GW are installed, centralized PV will remain mostly constant and distributed PV will increase slightly, shown figure 14. However, for scenario 2 where distributed investment costs are lowered to 15% difference from centralized, it is shown in figure 19 that network costs start to compensate as the penetration level increases, to finally install a similar amount of centralized PV and distributed PV.

Recent research has however shown that above a threshold (at very high penetration rate and with generators concentrated in a specific area and all of them feeding the distribution grid), the size of the transmission and distribution losses goes up again [MEND06].

Furthermore, figure 18 verifies this tendency and for 20 GW it will almost be entirely distributed PV. Therefore, distributed network costs equalize investment costs to finally reach cost competitiveness in relation to centralized PV.

According to Figures 16, 17 and 18, investment costs are a crucial factor that encourages installing distributed generation. Once this cost is aggravated enough, distribution costs will not differ regarding initial values, for low penetration levels.

Scenario 1, distributed investment costs are 30% higher than centralized investment costs

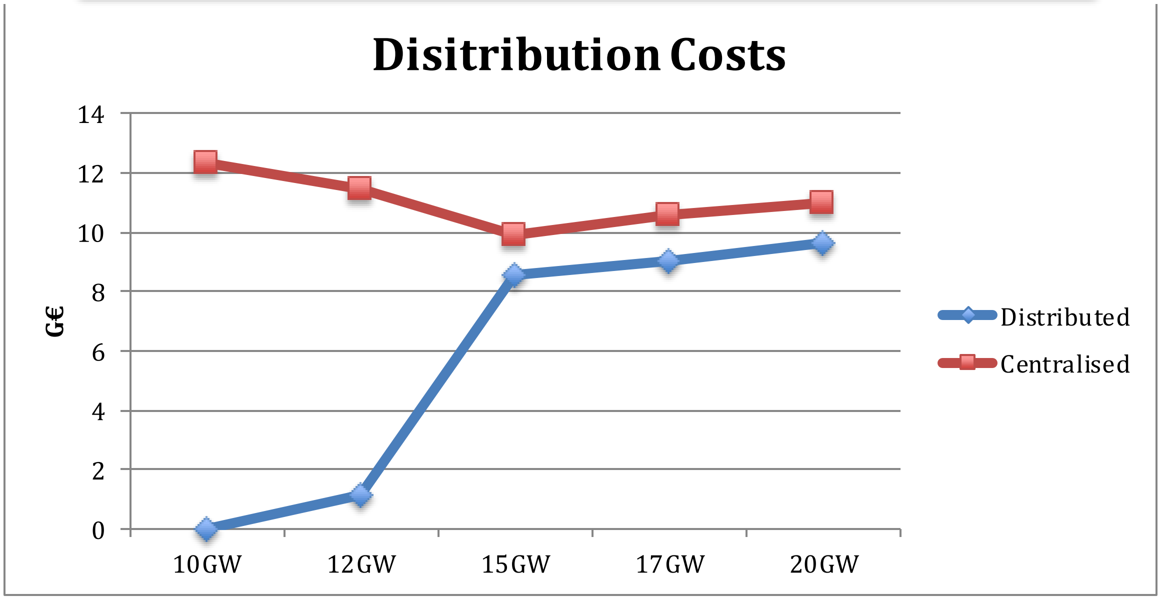


Figure 18.Total PV network costs for scenario 1
Source: Own Source

Scenario 2, distributed investment costs are 15% higher than centralized investment costs

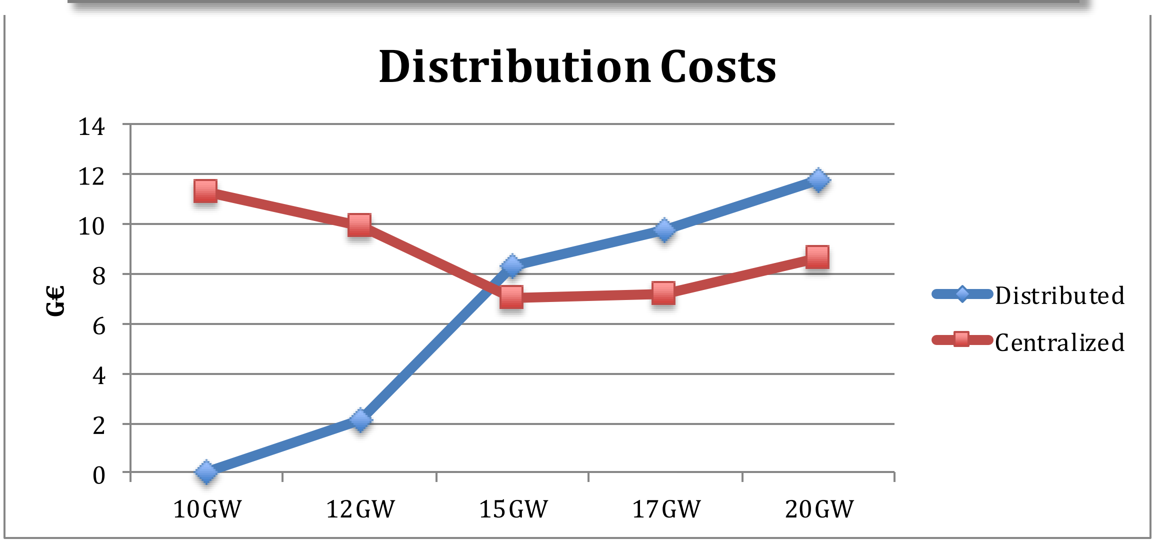


Figure 19.Total PV network costs for scenario 2
Source: Own Source

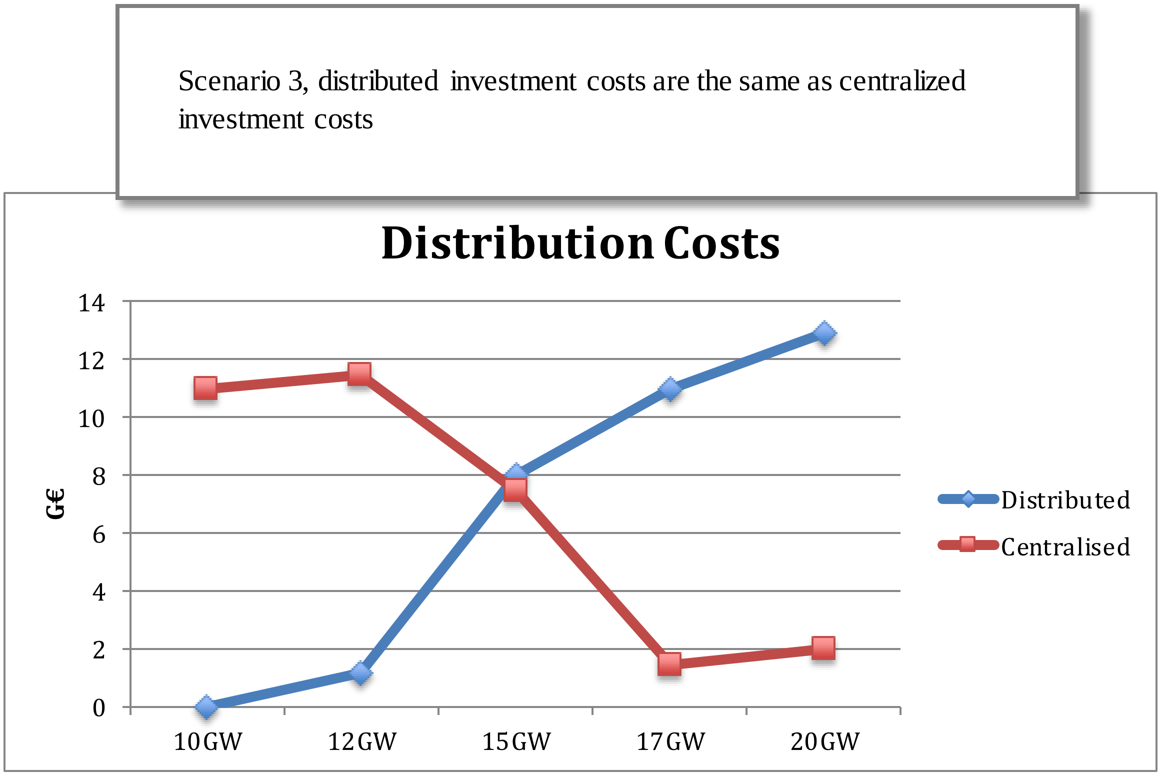


Figure 20.Total PV network costs for scenario 3
Source: Own Source

In conclusion, as for the results in the different scenarios, as distributed investment costs are increased, respect from centralized costs from one scenario to another, the costs distribution curve tends to tilt with a bigger slope, as costs increase. For scenario 2, we find that distributed PV is competitive vs. centralized PV for distributed investment costs 15% higher than centralized investment cost, and for the same investment costs, it will be preferable to install distributed PV for high generation in scenario 3.

As it was anticipated, investment costs are a cost driver for low generation as in figures 18, 19 it only installs centralized generation for 10 GW, as for high generation, network costs will overcome the others, as it becomes representative in figure 20 for 20 GW.

Given that decentralized generation will never be higher than centralized, and that network costs are cheaper for decentralized, if their costs become approximately the same at a generation point, it will be more optimum to install decentralized PV as well as centralized.

In figure 20 it is again represented scenario 2, where we find cost competitiveness for distributed PV in the final installed capacities (15 GW, 17 GW and 20 GW).

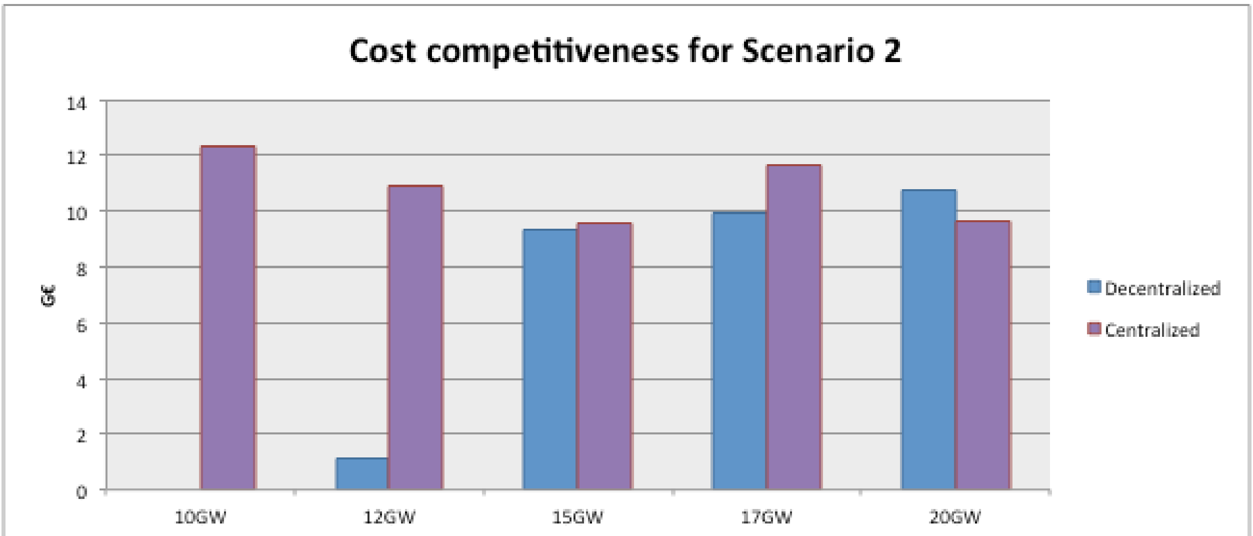


Figure 21. Most representative scenario for cost competitiveness
Source: Own Source

The results shown in figure 21 reveal that a significant penetration of PV generation is a relevant cost driver in distribution networks, assuming that the sample represents well the diversity of networks found in the electric industry.

8. CONCLUSIONS

The power sector is evolving with anticipation of increase in penetration of distributed generation, storage technologies and demand side participation. These will bring new opportunities for implementing innovative solutions for traditional issues such as demand driven network reinforcement, through locally satisfying of demand, using distributed resources.

Different study cases have been carried out depending on the different parameters reported previously. The main contribution of the study is to show how distributed resources reduce network costs and the competition with centralized resources at different penetration levels.

The first study case is the determination of how installing distributed PV in the energy model will affect the already existing capacities and their respective costs. It is concluded that for a considerable quantity of distributed generation, the model invests in renewables instead of gas, as a result of the cost optimization, as for an increase in installed capacity network costs tend to overcome investment costs. Investment costs are increased as operation and maintenance costs are slightly reduced. As investment costs are considerable taking into account the overall costs, we will have cost savings and a reduction in emission costs.

The second study case is the determination of cost competitiveness between centralized PV and decentralized PV. To obtain reasonable results it was necessary to model an objective function for networks costs to differentiate centralized PV from decentralized PV in the MASTER model. This function would optimize the amount of distributed generation necessary to find the cost competitiveness, which it results to be around 15 GW and for distributed investment costs 15% higher than centralized investment cost.

As shown in the results of the run case studies, the grid integration cost of PV is a function of PV penetration levels. It can be concluded from our studies that the higher the penetration level, the cost tends to be higher. This is expected since more deployment of new infrastructure may be needed to accommodate higher PV penetration.

9. REFERENCES

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10. ANNEX 1: Formulation basis

Equations and Constraints

Equation 1: PV Decentralized

$$Objective\ Function\ for\ Decentralised\ PV$$

$$Decentralised\ Costs\ =e=$$

$$0.4617\ *(\ NEWINSTALLCAP('CESOPHVDIWOTOTH')+ NEWINSTALLCAP('CESOPHVDIWOTIND'))$$

$$-(0.4617*\ NU\_DIS1('CESOPHVDIWOTOTH'))-(0.4617*\ NU\_DIS2('CESOPHVDIWOTIND')) - 0.8081\ *c+(0.8081\ *UC\_DIS1)-0.8081\ *e+(0.8081\ *UC\_DIS2)$$

$$+(\ 0.0004722\ *\ sum((phvdistrib,p,s,l)\ ,QPWR(phvdistrib,'CESOPHVDIWOTOTH',p,s,l) * D(p,s,l))-8.4998*c)$$

$$+(\ 0.0004722\ *\ sum((phvdistrib,p,s,l)\ ,QPWR(phvdistrib,'CESOPHVDIWOTIND',p,s,l) * D(p,s,l))-8.4998*e)\ ;$$

In this equation,
$\boldsymbol{NEWINSTALLCAP('CESOPHVDIWOTOTH')}$**,** Denotes for the new installed capactity
$\boldsymbol{QPWR}$, Is average quantity of energy flow

Equation 2: PV Centralized

$$REL\_OFVP\_PVCE\_COST\_P123..$$

$$OFVP\_PVCE\_COST\ =e=$$

$$(\ 0.4566\ *NEWINSTALLCAP('CESOPHVCEWT'))-(0.4566*\ NU\_CE('CESOPHVCEWT'));$$

In this equation,
$\boldsymbol{NEWINSTALLCAP('CESOPHVDIWOTOTH')}$, Denotes for the new installed capactity
$\boldsymbol{QPWR}$, Is average quantity of energy flow.

Logical propositions

A series of logical propositions to linearize final transport costs.

$x\delta$ $x \geq 0$ $\delta \in \{0,1\}$	Reemplazar $x\delta$ por y $\delta = 0 \rightarrow y = 0$ $\delta = 1 \rightarrow y = x$	$y \geq 0$ $y \leq M\delta$ $-x + y \leq 0$ $x - y + M\delta \leq M$ $x \leq M$